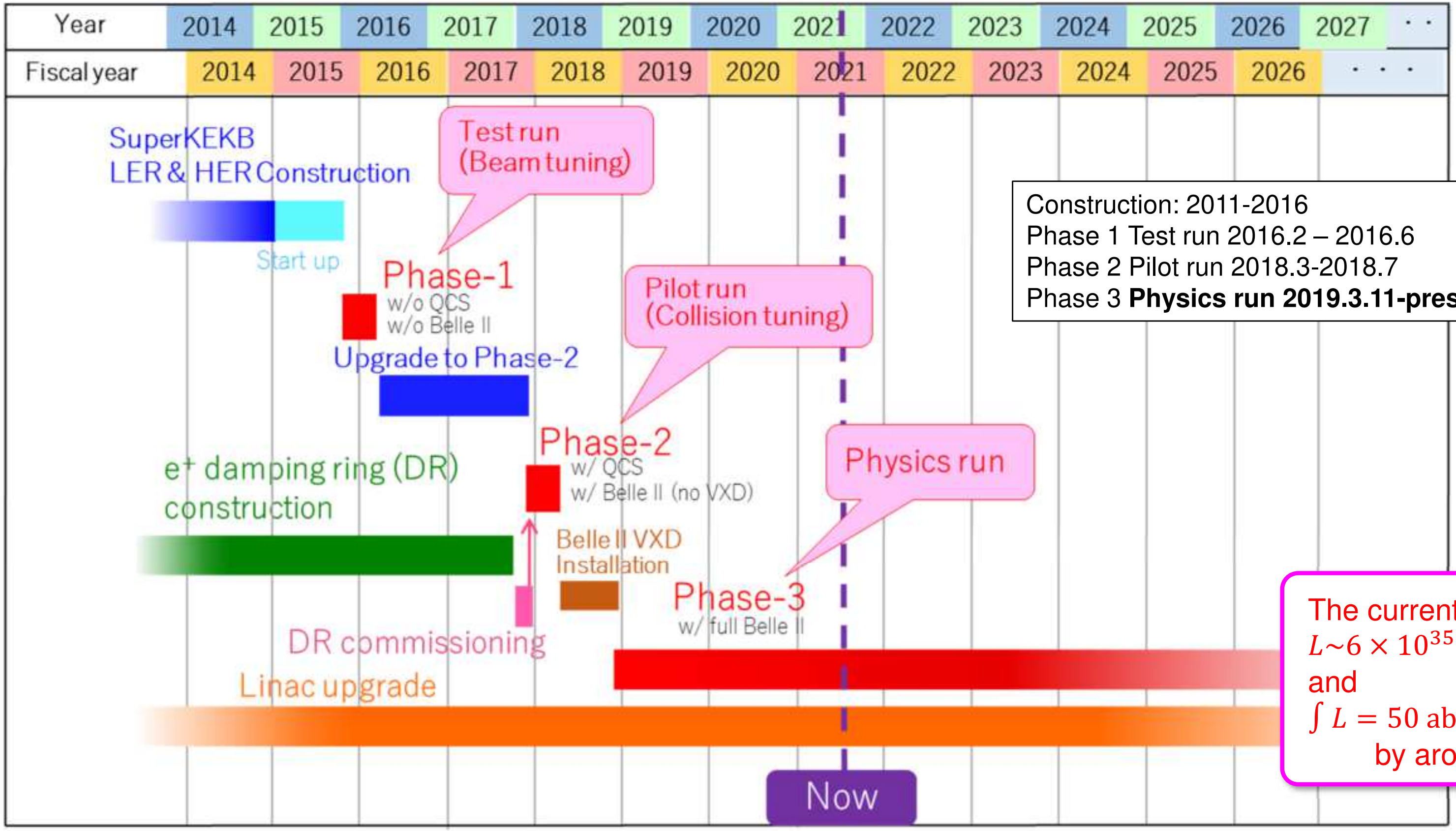
Discussions on the long-term operation plan in the last year

Y. Suetsugu
KEK

The 26th KEKB Review Meeting
09/02/2021

SuperKEKB project timeline

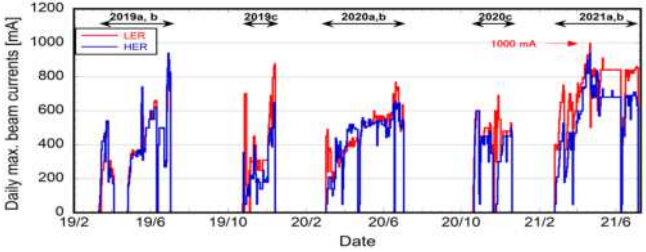


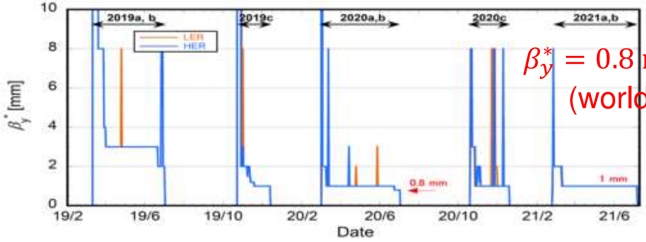
Construction: 2011-2016
Phase 1 Test run 2016.2 – 2016.6
Phase 2 Pilot run 2018.3-2018.7
Phase 3 **Physics run 2019.3.11-present**

The current goal:
$L \sim 6 \times 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
and
$\int L = 50\ \mathrm{ab}^{-1}$
by around 2031

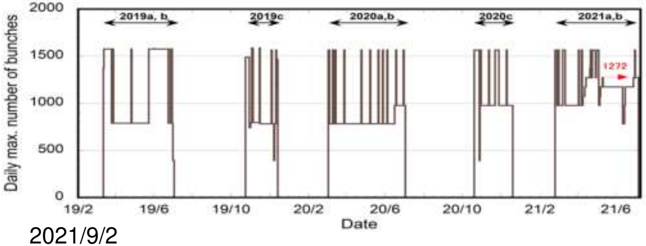
SuperKEKB achievements to date

- The performance has been improved steadily.
- SuperKEKB is already exploring uncharted territory!

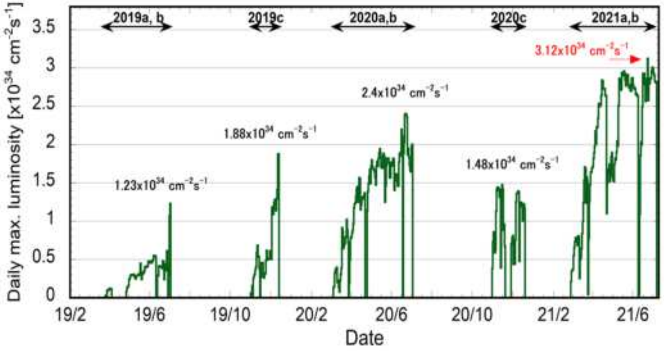




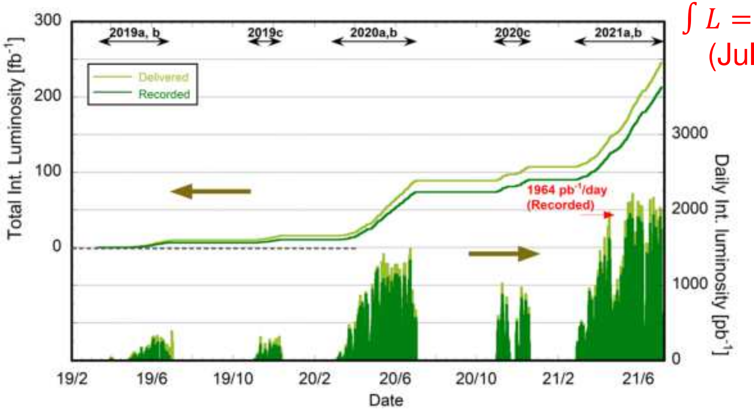
$\beta_y^* = 0.8\ \mathrm{mm}$
(world record)



$L_{peak} = 3.12 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
(world record)



$\int L = 213.5\ \mathrm{fb}^{-1}$
(July, 2021)

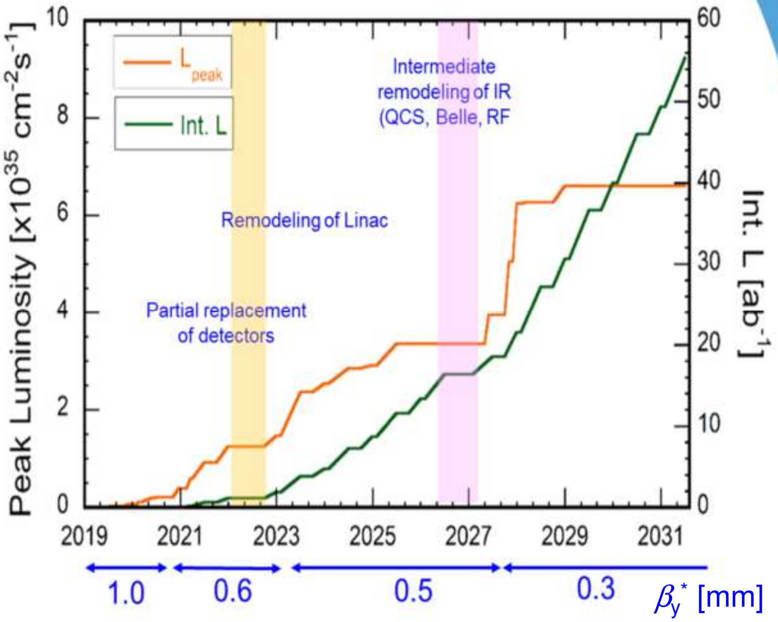


Challenges recognized in recent commissioning

- To improve the machine further to achieve the goal, however, various challenges as follows should be solved:
  1) Severe beam-beam effect (vertical beam size blow-up)
     - Vertical beam size (vertical emittance) blow-up has been observed at high bunch currents.
     - Relaxed by the crab-waist collision scheme, but it still remains.
  2) Shorter beam lifetime than expected in the design phase.
     - The maximum bunch currents are limited by the balance between the lifetime and the injection power.
     - The dynamic aperture is very small due to the beam-beam effect and crab-waist sextupoles, while the physical aperture is limited by the beam collimators.
  3) Lower bunch-current limit due to TMCI than expected.
     - The cause is higher impedance of beam collimators, where the apertures are smaller than the design values to suppress high background to Belle II.
  4) Low machine stability
     - Abnormal beam aborts, sometimes leading to the damage of collimators.
     - Operation efficiency during 2021ab, for example, was almost 0.5, lower than expected one, 0.65. (Main causes: machine tunings, machine troubles, maintenance, etc.).
  5) Aging of hardware and facilities, and so on.

Long-term operation plan

- Current operation plan (luminosity profile)
  - The current goal is to achieve
    $L{\sim}6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and
    $\int L = 50\ \mathrm{ab}^{-1}$ by around 2031, which requires an intermediate machine upgrade around 2026 (LS2) that improves the luminosity by a factor of 2-3.
  - The plan was adopted in the MEXT roadmap 2020.
  - The plan and profiles were assessed by the external review committees (Accelerator Review Committee (ARC, 2020/7) and BPAC (2020/6, 2021/3, 6))



- Over the next year or so, perform beam measurements to determine if the proposed upgrades are absolutely required to get to the design luminosity.
- Determine which technical studies need to be carried out now, before a decision can be made, within about 2 years. (Excerpt from the last ARC) (See Appendix A)

Long-term operation plan

- Based on the recommendations from these review committees, “Long-term operation plan meeting” (internal, Chair: H. Koiso) was launched in August, 2020. (See Appendix B)
- To solve the confronting challenges and to realize the plan, a variety of countermeasures have been proposed and discussed over the last year in various meetings, such as MDI (Machine Detector Interface) meeting (Chair: H. Nakayama), ITF (Injection Task Force) meeting (Chair: N. Iida), IR technical meeting (Chair: N. Ohuchi, K. Shibata) and so on, as well as the Long-term operation plan meeting.
- Key measures to improve luminosity and integrated luminosity
  - To improve luminosity
    - Increase injection power (injection efficiency, bunch charge) or improve beam lifetime (dynamic aperture and also physical aperture)
    - Improve beam-beam parameter (low emittance)
    - Relax TMCI limit (important if emittance is still large).
    - Lower background -> Wide collimator aperture (physical aperture)
  - To improve operation efficiency (Integrated luminosity)
    - Improve stability of machines
    - Increase efficiency of beam tuning (improvement tuning knobs)
    - Execute anti-aging plans for facilities

Planned countermeasures

- Major countermeasures discussed so far.
  - See Appendix C for some details.

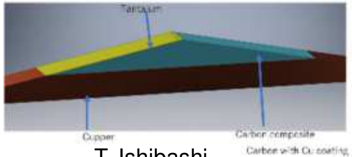
	Aim	Possible countermeasures
(1)	・Increase injection power (efficiency)	Linac upgrade to designed specification
		Large physical aperture at electron injection point (HER)
		Linac upgrade beyond designed specification
(2)	・Relax beam-beam effect ・Expand dynamic aperture	Utilizing rotatable sextuplole magnets (LER)
		“Perfect matching”
		QCS modification (Option#1): Move QC1RP to the far side of IP
		Larger scale QCS modification (Option #8)
(3)	・Suppress BG ・Expand physical aperture	QCS cryostat front panel modification and additional shield to IP bellows
		Optimization of collimator location
		Enlargemen of QCSR beam pipe (Option#3)
(4)	・Relax TMCI limit	“Non-linear collimator”
(5)	・Improve stability	Robust collimators
		Upgrade of beam abort system and loss monitor system
(6)	・Anti-aging measures	Preparation of standby machines and spares, repair of facilities, etc.

Planned countermeasures

- High-priority countermeasures before LS2

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Increase injection power (efficiency)	Linac upgrade to designed specification	Full spec injection (both power and quality)	On going sequentially.	
Relax beam-beam effect	Utilizing rotatable sextupole Magnets	Beam-beam parameter (emittance), beam lifetime	Ready. Need preparation of tuning knob. Knob tuning will be tried during 2021c.	
Improve stability	Robust collimator	Sustainability	On going sequentially. Need more R&D and beam test	
Improve stability	Upgrade of beam abort system and loss monitor system	Operation stability	On going sequentially with Belle II group.	
Anti-aging measures	Anti-aging measures	Operation efficiency (standby machine, repair of facilities)	On going sequentially. Especially for long shut down periods	

- Essential to achieve ~2×10^{35} cm^{-2}s^{-1} before LS2.



T. Ishibashi

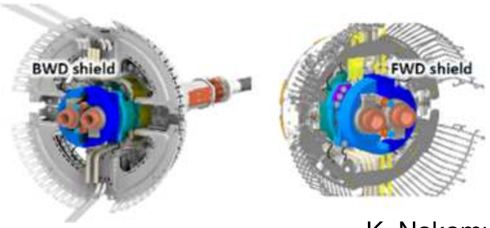
Rotatable Sextupole magnet

M. Masuzawa

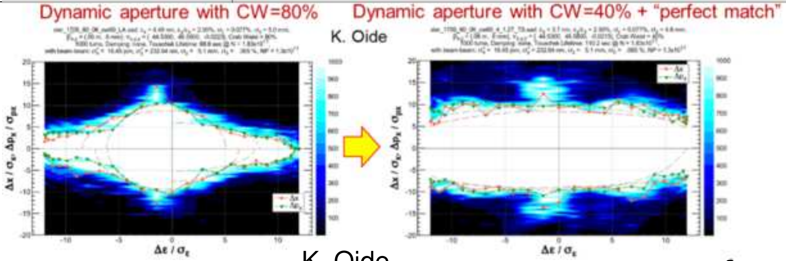
Planned countermeasures

- Possible countermeasures in LS1

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 / LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Increase injection power (efficiency)	Large physical aperture at electron injection point (HER)	HER Injection rate x #?	Need further estimation, simulation, design of beam pipes	
Expand dynamic aperture	“Perfect matching”	**LER beam lifetime (Tousheck) x ~1.5.**	Need further simulation, design, manufacturing of magnets and pipes	
Expand physical aperture Suppress BG	QCS cryostat front panel modification and additional shield to IP bellows	Background, Physical aperture, **TMCI limit x ~1.2**	**Production is on going. Will be ready by 2022**.	
Expand physical aperture Suppress BG	Optimization of collimator location	**Background x ~1/2 (Storage beam)**	On going. Need further simulation.	
Relax TMCI limit	“Non-linear collimator”	**TMCI limit x~2** **Background x ~1/2 (Storage beam)**	Need further simulation, design, manufacturing of magnets and pipes. **Production of PS has started.**	



K. Nakamura



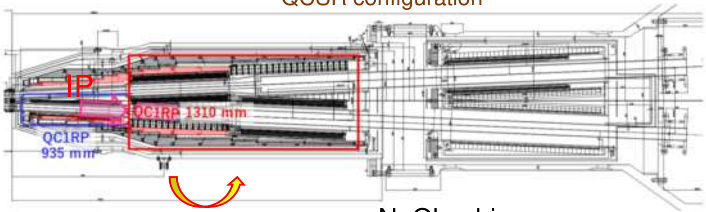
K. Oide

Planned countermeasures

- Possible countermeasures in LS2

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Widen dynamic aperture	QCS modification (Option#1): Move QC1RP to far side of IP	**Found to be no effect.**	**Will be not adopted**	
Expand physical aperture Lower BG	QCSR beam pipe enlargement (Option#3)	13.5 mm -> 15 or 18 mm, β_y^*=0.3 will be possible. But **no effect on dynamic aperture**, **TMCI limit x ~1.5.**	Need design, manufacturing of correction magnets and pipes	

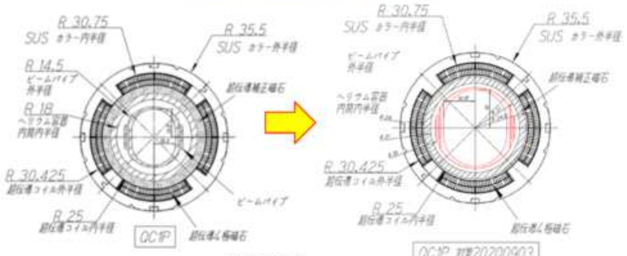
QCSR configuration



N. Ohuchi

Option #1

Cross section of QC1RP

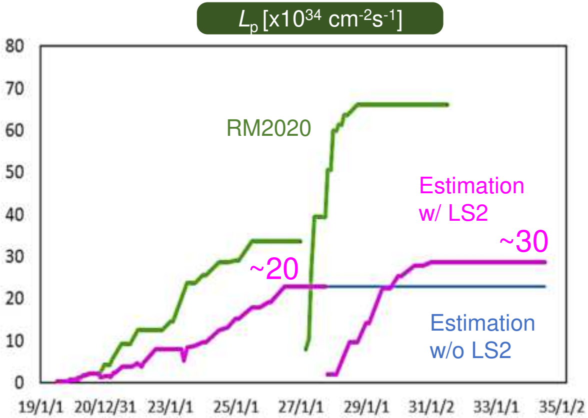


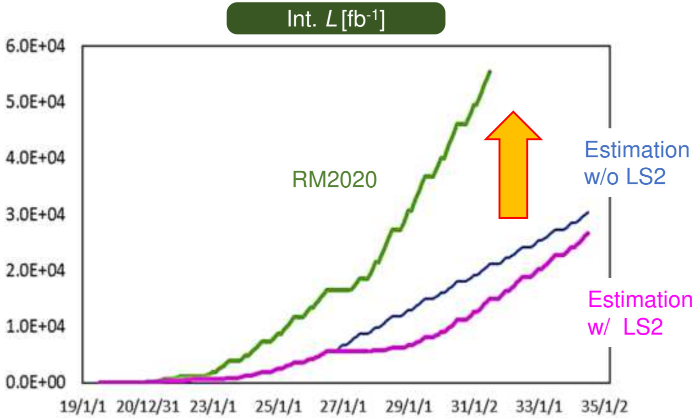
N. Ohuchi

Option #3

Preliminary luminosity estimation

- Estimated luminosity with countermeasures discussed so far.
  - Assumptions: Designed beam injection (after Linac upgrade) and vertical emittance (No TMCI limit), No background limit, Only Touschek lifetime. (See Appendix D.)





- Mainly due to the short beam lifetime (narrow dynamic aperture), the luminosity will be lower than expected.
- The ideas of the intermediate upgrade of IR around 2026 we have planed so far are not as satisfactory from the viewpoint of int. luminosity as given in RM2020.

⇒ More effective measures to boost up the luminosity is required!

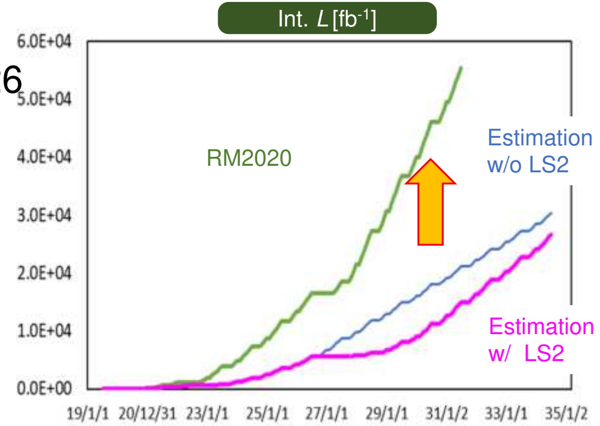
Future Plan

- We will continue the effort to find more effective (x2~3) measures, not limited to the IR but also to other parts of the MR and Linac, to maintain the target luminosity profile.
- Ideas of a more revolutionary upgrade including some modification of Belle II should be considered to reach even higher luminosity; this may require a longer time for R&D (~203x).
- On the other hand, some practical conclusion should be obtained before LS1 (2022~2023) on the feasibility and contents of the upgrade around 2026 (LS2), considering the preparation period of hardware.

- Create an **international task force (Coordinator: M. Masuzawa)** under the management of the KEK Accelerator Lab. and B promotion office (BPO) to pursue effective measures for recovering the luminosity profile and reaching target luminosity. (See Appendix E and Maszawa-san's talk next)

Summaries

- Enthusiastic discussions have been on going since last year to examine and realize the long-term plan presented in MEXT Roadmap2020.
- Although the performance of SuperKEKB has been improving steadily, various challenges should be solved to further improve the machine to achieve the goal.
- Against these challenges, various countermeasures have been proposed in various meetings based on the simulation and observations to solve them.
  - Some countermeasures were decided to be taken during LS1.
- However, the luminosity seems to be still lower than expected considering various limitations.
  - The ideas of the intermediate upgrade of IR around 2026 we have planed so far are not satisfactory.
- We have to continue to find more effective measures, not only limited to the IR but also including the other parts of MR and Linac to maintain the target profile.
- The international task force has been created especially to discuss ideas to boost up the luminosity by the intermediate upgrade.



We greatly appreciate your corporation!

Appendix A: Recommendations from ARC and BPAC (Excerpt)

Long-term operation plan

- Excerpt from KEKB Review Report (Long-term plan part) -1 (2020/7)
  - R7.2: Over the next year or so, perform beam measurements to determine if the proposed QCS upgrades with larger apertures are absolutely required to get to the design luminosity or, e.g., to half the design luminosity.
  - R7.6: Determine which technical studies (essential beam studies and QCS coil parameter studies) need to be carried out now, before a decision can be made, within about 2 years, on starting construction of new QCS quadrupoles.
  - R7.7: Determine the technical staffing and accelerator experts needed to construct the required hardware upgrades and examine if new technical staff will need to be trained or hired to design and execute these upgrades.

Long-term operation plan

- Excerpt from KEKB Review Report (Long-term plan part) -2 (2020/7)
  - R7.8: Evaluate a backup plan to simply increase the luminosity with the existing hardware to about 2-3x10^{35} $cm^{-2}s^{-1}$ (with small upgrades but without major upgrades and the associated long installation downtimes and serious recommissioning) and then integrate luminosity for about 10-12 years at 7-8 months per year to obtain an integrated luminosity of 50 ab^{-1} by 2032-2034.
  - R7.9: Present a detailed SuperKEKB upgrade plan with underlying reasoning and data at the next ARC meeting.
  - Detailed long-term upgrade plans should be finally decided once full performance with those upgrades is predicted within a quantitative performance model. This makes sure that the long-term quadrupole aperture is chosen wide enough, background sources and paths are understood, lower beam lifetime can be handled, impedance stays under control, and the collimator system is adequate.

Long-term operation plan

- Excerpt from BPAC Report (2020/6)
  - Based on the experience in operating SuperKEKB, the machine team has been developing ideas that could achieve the physics goal of the Belle II experiment with lower consumption of electricity . The committee understands that such an operation scenario over the next ten years was presented in the KEK submission to the MEXT Roadmap selection process, and finds this development timely and very attractive. Implementing such a plan requires an upgrade of the machine and detector. The BPAC strongly encourages a close collaboration between SuperKEKB and Belle II to further explore various ideas and conduct the necessary research and development work. Implementation of the necessary upgrade should then follow after positive evaluation of technical designs by the relevant committees. The BPAC is looking forward to hearing the progress in future meetings and strongly hopes for a positive outcome from the MEXT Roadmap selection.

Long-term operation plan

- Excerpt from BPAC Report (2021/3)
  - The SuperKEKB machine has been operating at higher luminosities with lower beam currents than those of the KEKB machine and the committee appreciates the continuous effort and improvements by the machine group for stable running of the machine. It appears that there are persistent obstacles, such as the increase of emittance for the high energy beam in the injection line, which prevent the machine from increasing luminosities without raising the background above the acceptable level for the experiment.
  - Another important issue on a relatively short time scale is the consolidation of the ageing machine components, in particular for the injector linac. The committee urges the machine group and the KEK management to address deferred maintenance in a timely manner by making an inventory of critical spare parts and making a replacement plan.
  - For the longer term, the committee thinks that the characteristics of the machine must be fully understood and exploited first to increase luminosities, before attempting a major hardware upgrade such as the new superconducting focusing quadrupole magnets (QCS) in the interaction region. Understanding of the hardware limitation of the machine would allow a prioritized and optimal upgrade path to be made.

Appendix B: Long-term operation plan meeting

Long-term operation plan meeting

- Four meetings have been held so far (~2021/2/4)
- The first meeting on 2020/8/21
  - The process so far [Y. Suetsugu]
  - Present status of QCS update project [N. Ohuchi]
  - Future plan of this meeting [H. Koiso, Chair]
- The second meeting on 2020/9/3
  - Summary of the first meeting [H. Koiso]
  - Examination status of the optics for QCS upgrade [A. Morita]
  - Crab waist, dynamic aperture and beam lifetime [K. Oide]
- The third meeting on 2020/9/26
  - Effect of IR Model V-20-20A (large physical aperture in QC1) on the beam optics [H. Sugimoto]
  - Examination of QC0P (Permanent magnet) [A. Morita]
  - Luminosity and lifetime (update) [K. Oide]
  - Effect of the enlarged physical aperture in QC1P on MDI mechanical design and background [H. Nakayama]
  - On flange at the top of QCS cryostat [N. Ohuchi]
  - Dependence of the injection efficiency on β_y^* [Y. Funakoshi]

Long-term operation plan meeting

- The fourth meeting on 2021/1/22
  - Progress report on QCS of upgrade project [N. Ohuchi]
  - LER dynamic aperture and luminosity (update) [K. Oide]
  - Status, issues and future plan of BT and Linac from a viewpoint of beam commissioning [N. Iida]
  - Middle and long-term outlook on injection efficiency and luminosity [Y. Funakoshi]
- The fifth meeting on 2021/2/17
  - Mid-long term plan at the injector linac [K. Furukawa]
  - Long-term plan at BT and DR [M. Tawada]
  - Remarks on injection issues discussed in the magnet group [Ohki]
  - Long-term strategy of beam collimators [T. Ishibashi and S. Terui]
- The sixth meeting on 2021/3/25
  - Upgrade plan of Linac positron source, pulsed magnets etc. (1) [Y. Enomoto]
  - Expectation of Luminosity [K. Nakamura]
  - Nonlinear collimator for LER in a dedicated section (1) [K. Oide]

Long-term operation plan meeting

- The seventh meeting on 2021/5/14
  - Upgrade plan of Linac positron source, pulsed magnets etc. (2) [Y. Enomoto]
  - Nonlinear collimator for LER in a dedicated section (2) [K. Oide]
  - Effect of collimator aperture on beam lifetime (LER) [Y. Funakoshi]
  - Current (intermediate) summary and future plan [Y. Suetsugu]
- The eighth meeting on 2021/8/27
  - Study results on semi-perfect matching [K. Oide]
  - RF system and possible beam currents [K. Akai]
  - Long-term plan of RF system [K. Watanabe]
  - Upgrade items and their persons in charge [K. Shibata]
- The nineth meeting on 2021/9 [planed]
  - Upgrade of RF gun laser system for high charge low emittance electron beam [R. Zhang]
  - R&D on RF tubes for high-electric field stable acceleration [H. Ego]

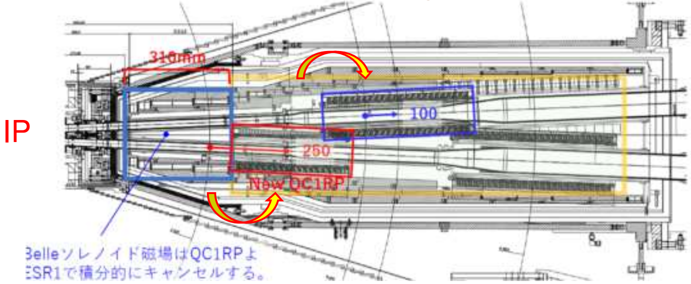
Appendix C: Countermeasures discussed so far

(1) QCS modification (#1)

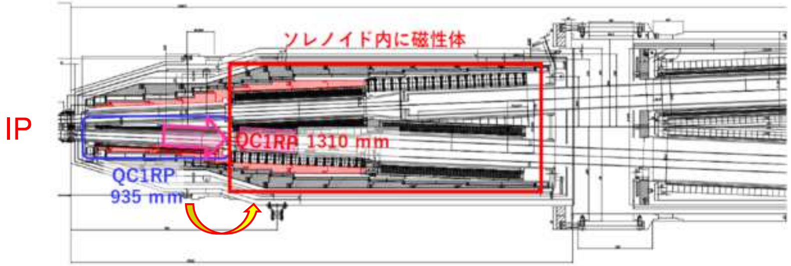
- Modification of QCS to avoid interference between the quadrupole magnetic field and the Belle II solenoid field: A promising method to mitigate the narrow dynamic aperture in LER
- Two ideas to relocate QC1P to the places farther from IP were examined.
  (1) Retract QC1RP (QC1LP) and QC1RE (QC1LE) 250 mm and 100 mm, respectively.
  (2) Retract QC1RP 375 mm.
- The radius of beam pipe inside QC1RP can be enlarged from 13.5 mm to 27 or 30 mm.
- However, it was found by simulations that little improvement in the dynamic aperture was expected even without beam-beam effect.
- Low solenoid field (1.5 T → 1.2 T) had also no improvement.

QCSR configuration

N. Ohuchi



QCSR configuration



Countermeasures discussed so far

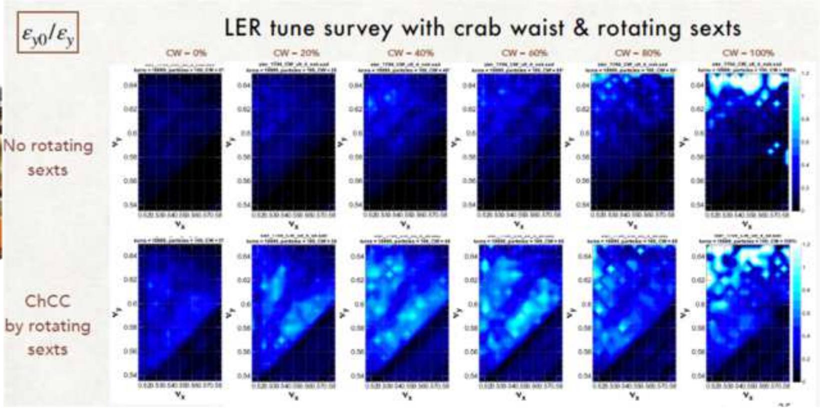
(2) Rotatable sextupole magnets

- It was also found in a simulation that the narrow dynamic aperture will be cured using the rotatable-sextupole magnets installed in the local correction region at Tsukuba (K. Oide).
- Eight rotatable sextupole magnets have been already installed. The operation check has been completed for each magnet.
- 2021a run was operated with a fixed angle of rotation.
- The effect has not been studied well.
- One problem in using these magnets is that it is now hardly possible to rotate them with beam. In other words, we cannot fully use them as a tuning knob.
- Developing a new software to rotate them synchronously is on going.
- IP chromatic coupling correction will be tried during 2021c run.

K. Oide (2021/6)

Rotatable Sextupole magnet

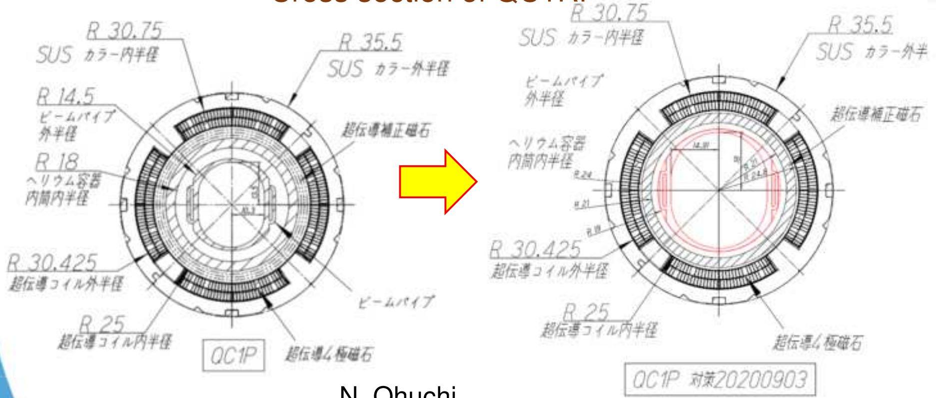
M. Masuzawa



(3) QCS modification (Option #3)

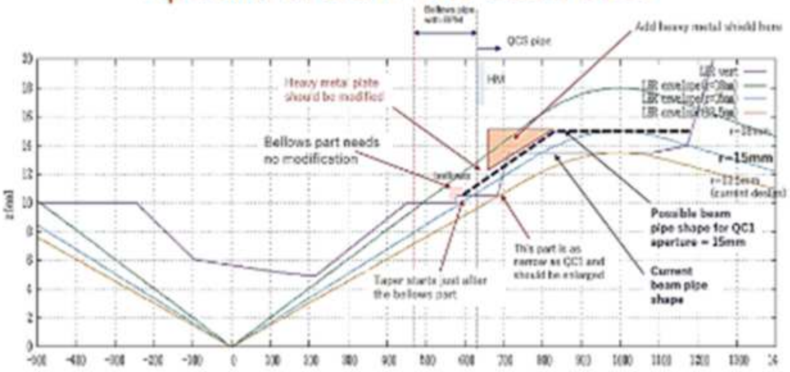
- Enlarge vertical aperture of beam pipes in QC1P without changing the boundary conditions between QCS and Belle detector.
- It is expected to increase physical aperture and then increase beam lifetime determined by the physical aperture, and also to reduce background.
  - Low background -> large aperture at beam collimators -> relax TMCI limit.
- Correction magnets are relocated to outside of the main quadrupole magnets.
- The inner diameter can be enlarged from 13.5 mm to 18 mm geometrically (QC1P).
- However, it was found by simulations that little improvement in the dynamic aperture was expected.
- The modification will be possible after 2026 even at the shortest case.

Cross section of QC1RP



N. Ohuchi

Aperture of QC1P and beam sizes

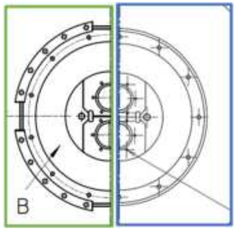


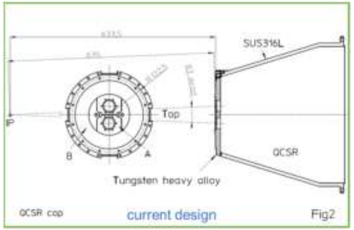
H. Nakayama

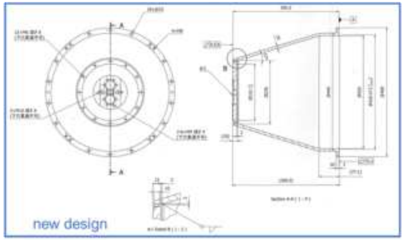
(4) QCS cryostat front panel modification and additional shield to IP bellows

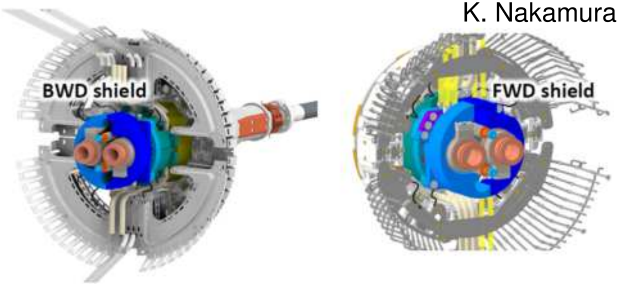
- Make rooms for cables of Belle II detectors.
- Exchange plate material from tungsten to stainless-steel to reduce the beam background.
- Add new radiation shield inside the cryostat.
- FWD and BWD bellows shields were also developed. In the current mechanics, there is no beam BG shield around the bellows pipes and a fraction of BG go into CDC and TOP from these regions.
- The preparation for LS1 is on going together with Belle II group.

K. Nakamura









Single-beam BG (SAD input with βy^*=1mm)

	LER Coulomb	LER Touschek	HER Coulomb	HER Touschek
CDC	27.77 ± 0.06%	13.00 ± 0.05%	29.03 ± 0.13%	24.50 ± 0.04%
TOP	23.43 ± 0.20%	9.93 ± 0.16%	19.70 ± 0.50%	20.74 ± 0.15%

Luminosity BG

	TwoPhoton	BBBrem	BHWide	BHWide_LA
CDC	29.15 ± 0.04%	50.44 ± 0.16%	29.98 ± 0.03%	-1.55 ± 0.17%
TOP	15.61 ± 0.18%	25.29 ± 0.91%	13.47 ± 0.14%	-3.33 ± 0.[illegible]%

2021/9/2

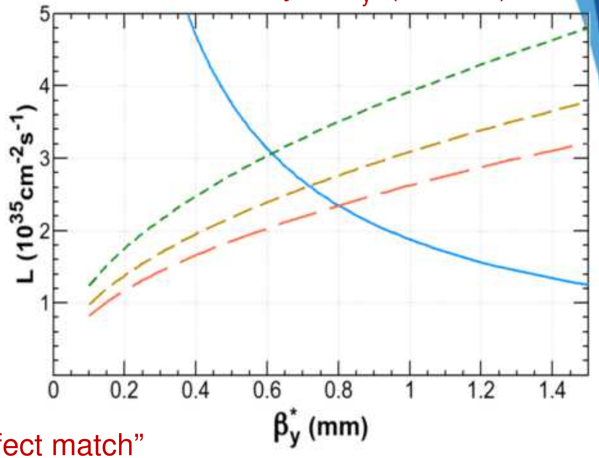
K. Shibata 2021/3/4

Countermeasures discussed so far

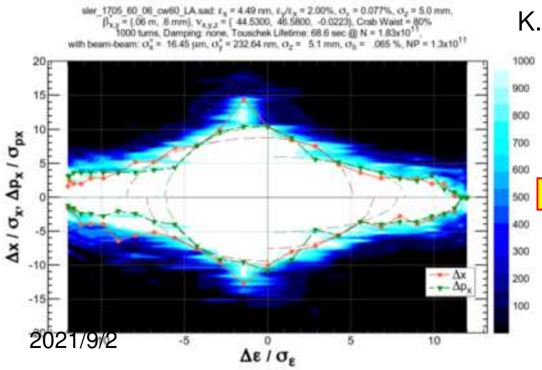
(5) Perfect matching

- Beam simulations with beam-beam effect have shown that "perfect matching" of LER optics significantly increases dynamic aperture (about 60%) and improves luminosity (K. Oide and H. Koiso)
- Specific studies are to be completed, but there is a possibility that this can be achieved with about four normal quadrupole and four skew quadrupole electromagnets.
- An equivalent electromagnet power supply is also required.
- New production of beam pipe for skew quadrupole electromagnet is required.
- Work during a long-term shutdown, LS1 or LS2.

Luminosity vs b_y^* (K. Oide)

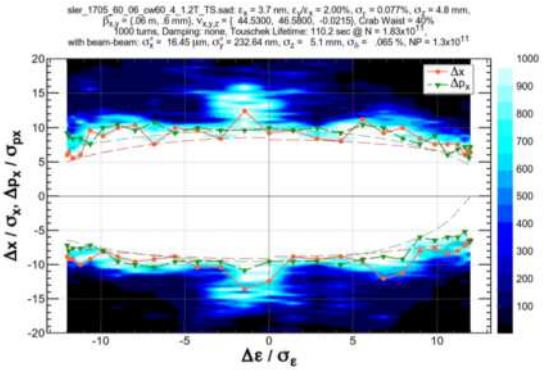


Dynamic aperture with CW=80%



K. Oide

Dynamic aperture with CW=40% + "perfect match"

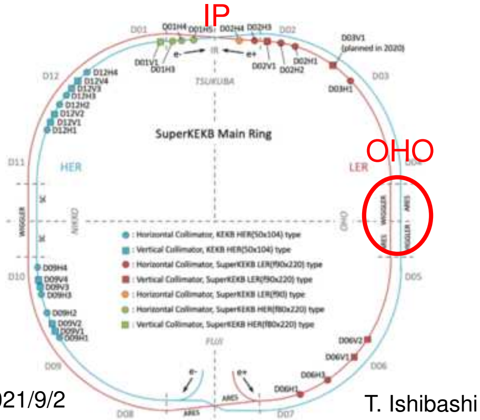


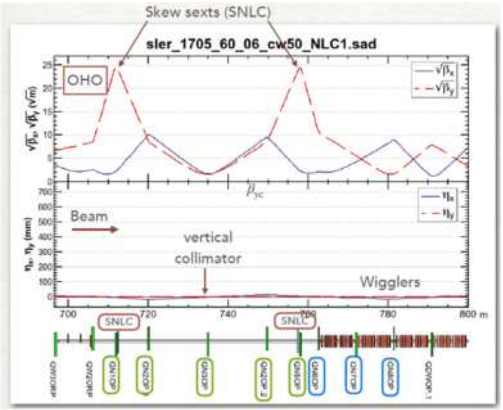
"Perfect match":
- Phase shifts between SLYTRP2/SLYTLP1 and IP are just 0.5 (x) and 0.75 (y).
- The values of β_x and β_y at the center of four SLY（SLYTLP1&2, SLYTLP1&2）are set to be the same, respectively.

(6) Non-linear collimator

- A vertical-type collimator, called as “non-linear collimator”, is located between a pair of specified skew-sextupole magnets. The non-linear vertical kicks by the magnet are utilized to enlarge the vertical displacement of particles at small β_y section, which will reduce the affect of collimator impedance and mitigate TMCI (K. Oide)
- The collimator will be installed at after the injection point, before the IP and the dispersion-free section, such as OHO straight section.
- Vertical phase advance of 0.25 between the sextupole magnets and the IP is possible, which reduce beam background.
- The dynamic aperture looks fine so far by simulation.
- The preparation has started to install the non-linear collimator during LS1.

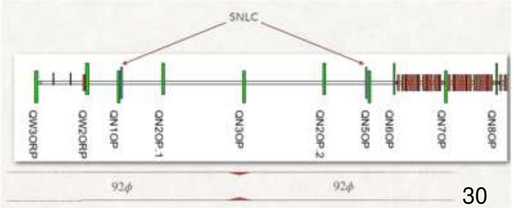
K. Oide





Reported by K. Yoshihara @ HCG on Mar. 23

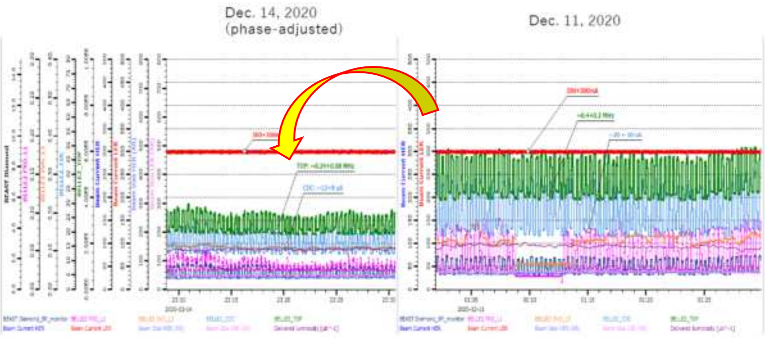
	y_c (mm)	β_{yc} (m)
D06V1	2.03	67.3
D06V2	2.42	20.6
D03V1	8.02	17.0
D02V1	1.27	13.9
NLC @ OHO	8.5	2.9

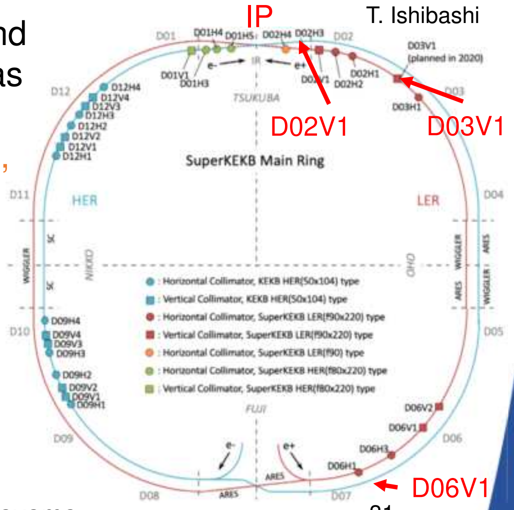


Countermeasures discussed so far

(7) Collimators: Optimization of location

- Background will be suppressed by optimizing the locations of beam collimators.
- Example 1
  - A new LER optics, where the phase advance between D03V1 and D02V1 collimators is (half-) integer was tried in 2020c run [$\Delta\nu_y$(D06V1 – D02V1) = 16.0, $\Delta\nu_y$(D03V1-D02V1)=3.5]
  - Aiming also to protect D02V1 by not only D06V1 but also D03V1.
  - TOP storage BG (beam-gas Coulomb) decreased by 30~40%. However, effect of impedance of collimators (especially D06V1 with carbon jaws) became prominent in this case (2020c).
- Example 2
  - Another optics, where the phase advances between QCS1, D06V1 and D02V1 are (half-) integer, is also said to reduce background (beam gas Coulomb) by 40%.
  - D02V1 collimator will be relocated during the 2021 summer shutdown, and effect will be checked during 2021c run.



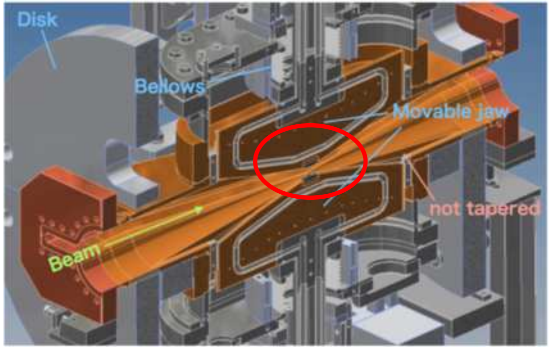


2020/12/14, Nakayama

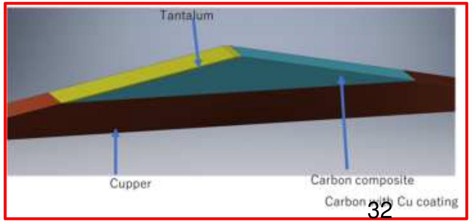
Countermeasures discussed so far

(8) Collimators: Low-impedance and robust collimator

- Collimator heads have been damaged several times by beam during heavy beam loss.
- The cause of the beam loss is not clear, but could be so-called “dust event”.
- New D06V1 collimator (carbon jaws, called “Low-Z collimator”), which was located at the place where the phase advance from D02V1 is integer, and was expected to protect D02V1 from strayed beams, but it did not work (2020c). Furthermore, high impedance of the carbon head induced the heavy TMCI.
- New low-impedance and robust collimator is required for stable operation.
- A test model, composed of tantalum and carbon with copper coating, will be installed during 2021 summer shutdown, and will be tested during 2021b run.
- The clarification of the beam loss mechanism is also important. Upgrade of loss-monitor system is under consideration (see (12)).



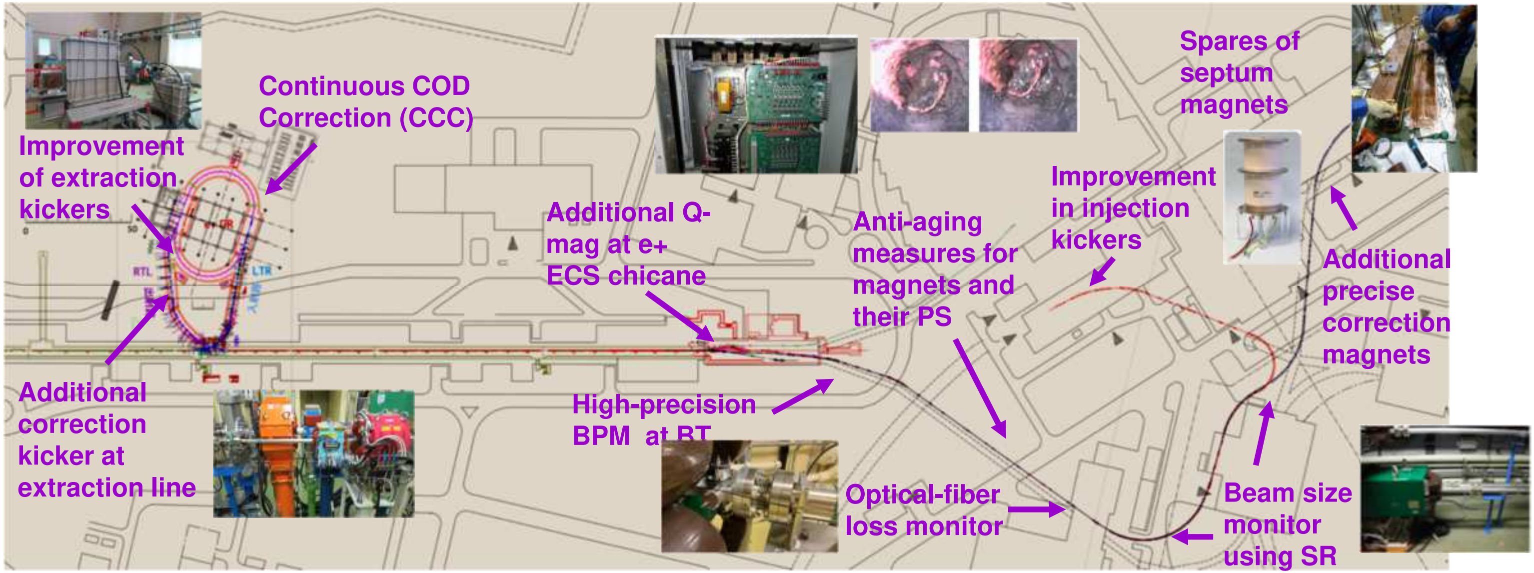
Carbon head



Countermeasures discussed so far

(9) BT (Beam Transport) line and DR upgrade: on going sequentially

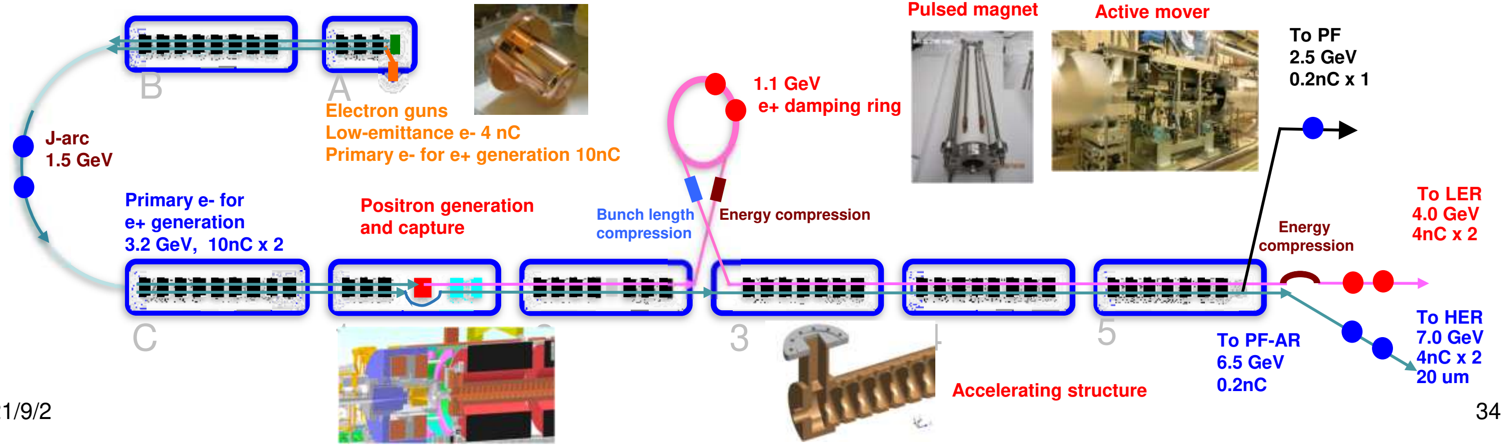
- Improvement of extraction kickers
- Additional correction kicker at extraction line
- Spares of septum magnets
- Anti-aging measures for magnets and their PS
- Improvement in injection kickers
- Beam diagnosis lines using SR
- Optical fiber loss monitor
- Additional Q-mag at ECS chicane
- High-precision BPM



Countermeasures discussed so far

(10) Linac upgrade up to designed specification: on going sequentially

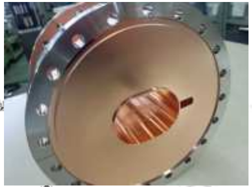
- Upgrade to the designed specification (4 nC/bunch, 2 bunches, 25 Hz repetition with an efficiency of 80%) is mandatory.
- Low-emittance, high-charge and stable RF gun.
- Efficient positron capturing.
- Upgrade of accelerating structure is on going.
- Active mover for magnets and accelerating cavities to control emittance growth due to wake field.
- Beam collimators to cut beam halo.
- Additional ECS (Energy Compression System) for electron beam.
- More pulse magnets to supply higher beam.
- Measure against trace amounts of PCB (required by LAW)



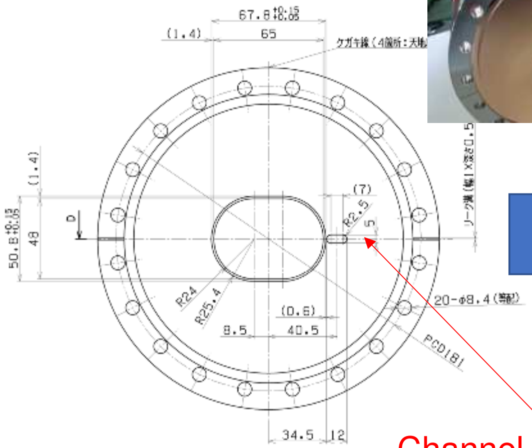
Countermeasures discussed so far

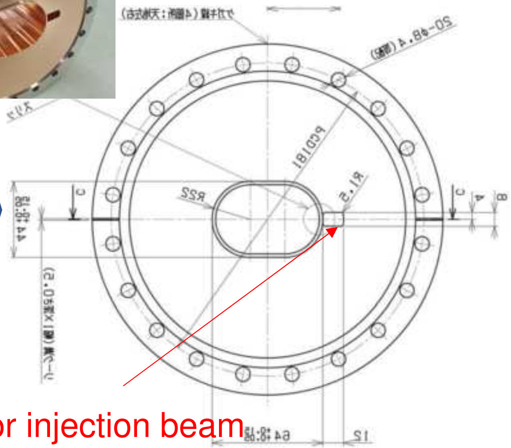
(11) Large physical aperture for injection beam (HER)

- One of countermeasures to improve the injection efficiency for HER. (see (9))
- Enlarge physical aperture for the injection beam.
- Reduction of the residual radioactivity there is expected.
- The efficiency should be evaluated more specifically.
- Understanding the actual beam orbit of injection beam and monitoring of the output of septum magnets are also required.

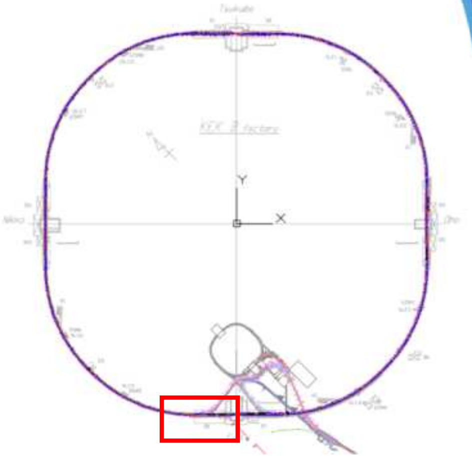


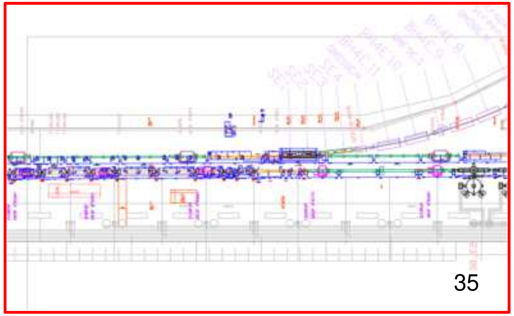
(Present HER)





(Present LER)

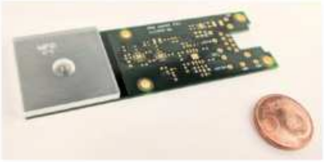


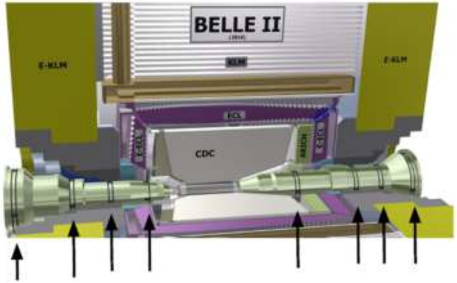


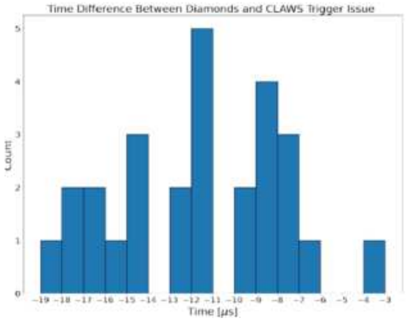
Channel for injection beam

(12) Improvement of beam abort system and loss monitoring system

- Rapid (~10 μs) heavy beam losses have been observed in LER and also HER.
- They have sometimes resulted in damages of collimator, QCS quenches and heavy damages to SVD.
- The cause of them, however, have not been well clarified, but one possibility has been said to be a dust event (i.e., beam loss due to the collision of circulating beams with dust in beam pipe).
- The mechanism of the beam loss should be clarified for stable operation at high beam currents.
- The beam abort system have been greatly improved, and now the beam can be aborted within 30~40 μs after a beam-abort trigger. But the beam loss was faster than that time.
- The setup of a beam loss monitor system to localize the energy-loss point is planned using PIN diodes (or diamond sensors) at collimators.
- It was reported that a beam-abort trigger could be issued ~8 μs faster than the present DIAMOND sensors by using CLAWS (sCintillation Light And Waveform Sensors) (I. Popov). The system has been in operation since 2021b run.







Countermeasures discussed so far

(13) Anti-aging measures

- Leaking roofs, corroded equipment's such as cooling system for RF
- MR power supply building and ancillary equipment are very old.
- Leakage may cover the power supply and interrupt operation.
- First-aid measures have been taken, such as installing a roof inside, but drastic measures are required to prevent rain leaks in the power supply building.
- Further, for example, corrosion of the klystron cooling system is often in a dangerous state.
- Some of the electromagnets and power supplies of the BT (Beam Transport Route) have been used since the Tristan era, and they are very old.
- The amount of cooling water is also frequently reduced, and the operation is interrupted.
- It has been confirmed that the inside of the cooling water pipe is clogged with copper oxide. If nothing is done, it will hinder driving.

Corrosion of cooling fan for RF system

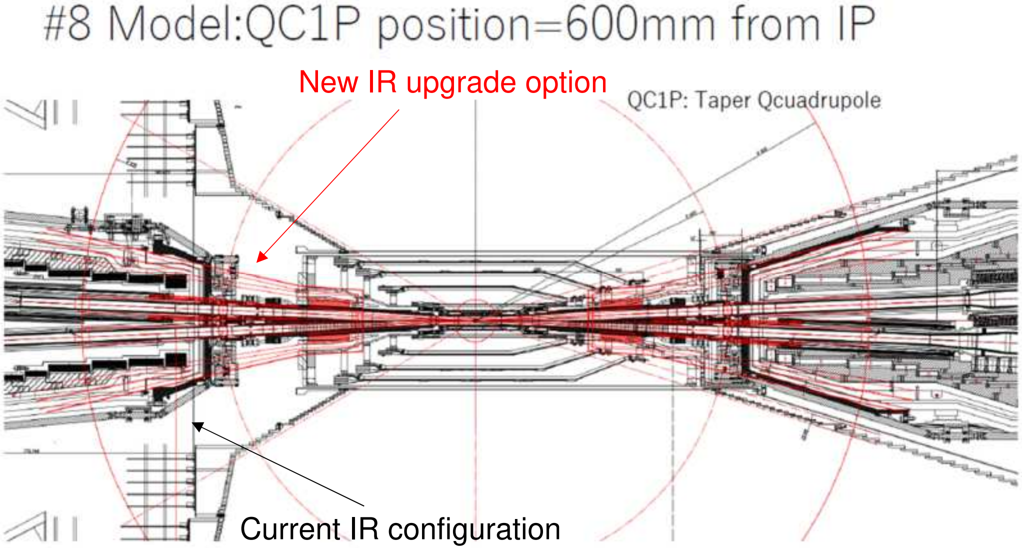
Water leak of MR power supply building

BT

Countermeasures discussed so far

(14) Large scale modification of IR (Option #8)

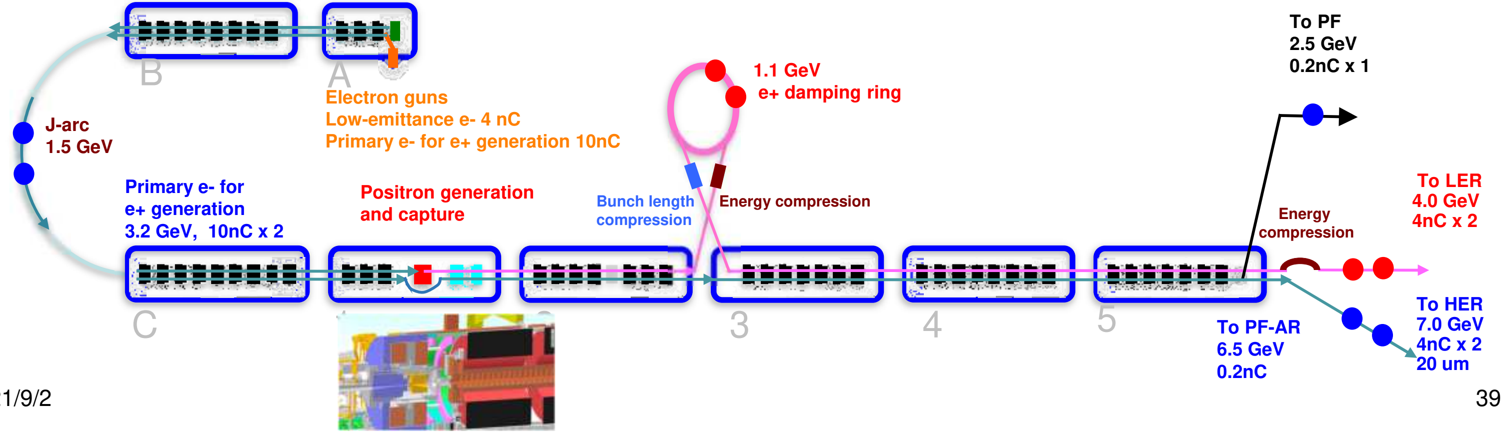
- Dynamic aperture increases as the distance between IP and QC1P decreases.
- To get sufficient effect, twice the beam lifetime for example, it is required to make distance between IP and QC1RP half.
- QCS magnets will be moved forward as much as possible while keeping the 17-degree-lines.
- More drastic IR upgrade, including Belle II upgrade, will be required.
- The R&Ds will take more than ten years or more.



N. Ohuchi, 2021/2/18

(15) Linac upgrade to beyond designed specification

- For e+, for example (by Y. Enomoto)
  - Increase FC current
  - Increase primary electron current
  - Increase accelerating field gradient
  - Optimize FC structure
  - Adopt moving target (pass e+ and e- beams on the same orbit)
  - Shorten the distance between FC and the first accelerating structure
  - Put electron gun after J-arc to increase bunch charge.
  - Use L-banc accelerating structure to increase aperture.
  - Use super-conducting FC to increase the magnetic field.



Appendix D: Luminosities under bunch-current limitations

Luminosities under bunch-current limitations

- The challenges add new bunch-current limits in addition to original RF-power and hardware limits to the operation, and will limit the luminosity.
  - Lifetime (injection power) limit based on the formula presented by K. Oide.

$$i_{b+}^{inj} = \sqrt{\epsilon_+ I_+^{inj} f_0 \frac{C_+^i \beta_y^* \sqrt{\varepsilon_y}}{N_b}} \qquad i_{b-}^{inj} = \sqrt{\epsilon_- I_-^{inj} f_0 \frac{C_-^i \beta_y^* \sqrt{\varepsilon_y}}{N_b}} \qquad \begin{array}{l} C_+^i = 3.6 \times 10^7 \\ C_-^i = 1.2 \times 10^8 \end{array}$$

  - TMCI limit $\quad i_{b+}^{tmci} = 1.4\ mA \quad i_{b-}^{tmci} = 1.5\ mA$
  - RF power limit $\quad i_{b+}^{RF} = \frac{I_+^{max}}{N_b} \quad i_{b-}^{RF} = \frac{I_-^{max}}{N_b}$

    I_+^{max}=2.59 A, I_-^{max} = 1.87 A before LS2

    I_+^{max}=2.82 A, I_-^{max} = 2.04 A after LS2
  - Hardware limit (for example by BPM)

$$i_{b+}^{hard} = 2\ mA \qquad i_{b-}^{hard} = 2\ mA$$

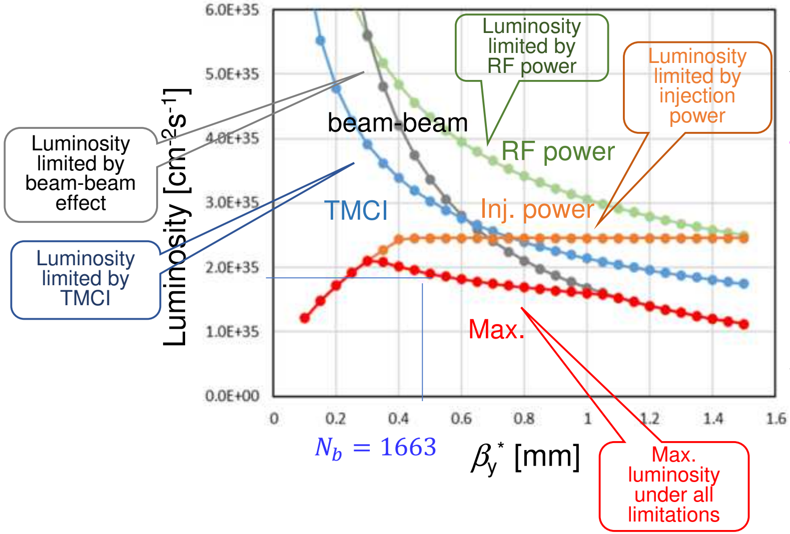
- Emittance (ε_y) is also a key parameter.
- Luminosity formula

$$L = \frac{1}{4\pi e^2 f_0 \sin\phi_c \sigma_z} \frac{N_b i_{b+} i_{b-}}{\sqrt{\beta_y^* \varepsilon_y}}$$

$$L_\xi = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_{y\mp}^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*} \sim \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$ (when limited by beam-beam parameter, ξ_y)

Luminosities under bunch-current limitations

- The luminosities under these bunch-current limitations were estimated by H. Nakayama and K. Nakamura.
  - Reported in MDI meeting, IR technical meeting, and LTOP meeting.
  - Here, the maximum luminosity was searched by scanning N_b (500~2500) for each β_y^*.
  - Assumptions:
    - Background does not matter.
    - Beam-beam parameter (ξ_y) and emittance (ε_y) are constant (no dependence on β_y^*).
    - Beam lifetime is determined by Touschek lifetime (due to dynamic aperture).
    - Beam current ratio of HER to LER is free.
- The calculation is not a strict simulation, but will give some guideline of achievable luminosities under these limitations.



$I_+^{max} = 2.59$ A, $I_-^{max} = 1.87$ A — Max. beam currents

$\sigma_z = 6.5$ mm — Bunch length

$N_b^{max} = 2500$ — Max. number of bunches

$\varepsilon_y = 20$ pm — Vertical emittance

$\xi_{y+}^{max} = 0.075$ — LER ver. beam-beam parameter

$C_+^i = 3.6 \times 10^7$, $C_-^i = 1.2 \times 10^8$ — Lifetime parameter

$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$ — Inj. efficiency

$q_+^{inj} = q_-^{inj} = 4$ nC — Inj. bunch charge

$N_{b+}^{inj} = N_{b-}^{inj} = 2$ — Inj. number of bunches

$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz — Inj. repetition rate

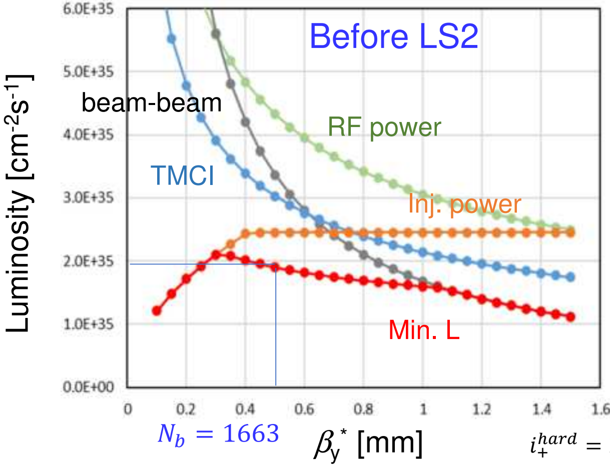
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA — Hardware limit

$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA — TMCI limit

Luminosities under bunch-current limitations

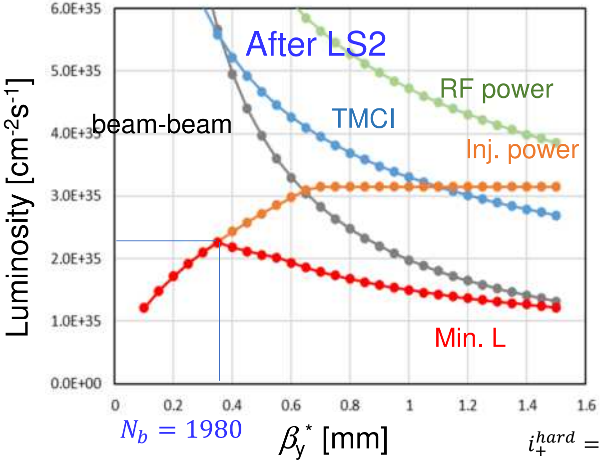
- The maximum luminosities before and after LS2 were estimated using possible parameters.
    - Assumptions: full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%. (After Linac upgrade)
    - Designed vertical emittance (No TMCI limit), No background limit, Only Touschek lifetime.

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.9x10^{35}** [cm^{-2}s^{-1}]



$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 20$ pm
$\xi_{y+}^{max} = 0.075$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA

- **After LS2**($\beta_y^* \geq 0.3$ mm), **L = 2.3x10^{35}** [cm^{-2}s^{-1}]



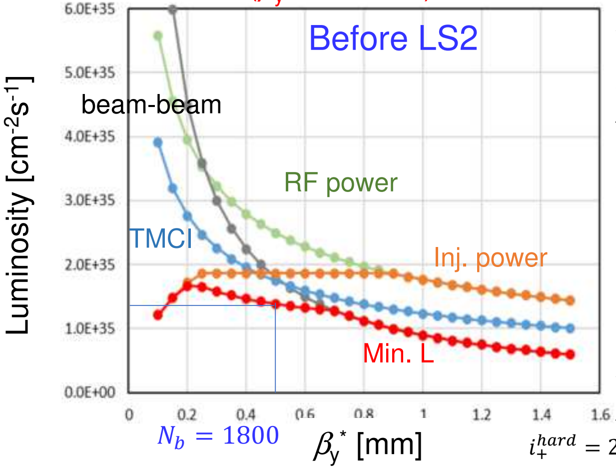
$I_+^{max} = 2.82$ A
$I_-^{max} = 2.04$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 10$ pm
$\xi_{y+}^{max} = 0.081$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA

Luminosities under bunch-current limitations

- The maximum luminosities before and after LS2 were calculated using possible parameters.
  - Assumptions: full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%. (After Linac upgrade)
  - No background limit, Only Touschek lifetime.

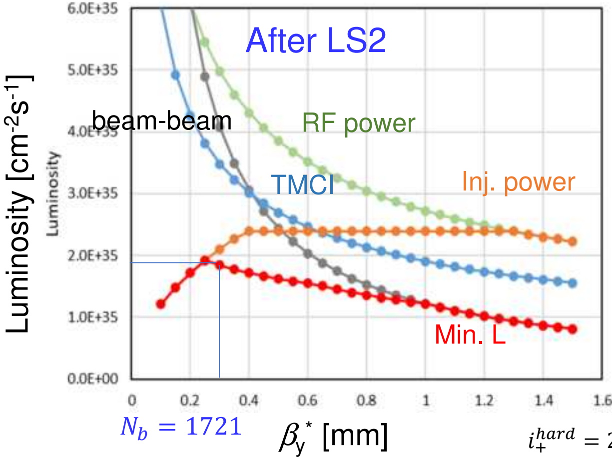
- Larger ε_y

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.4x10^35** [cm^{-2}s^{-1}]



$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 60$ pm
$\xi_{y+}^{max} = 0.04$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

- **After LS2**($\beta_y^* \geq 0.3$ mm), **L = 1.9x10^35** [cm^{-2}s^{-1}]



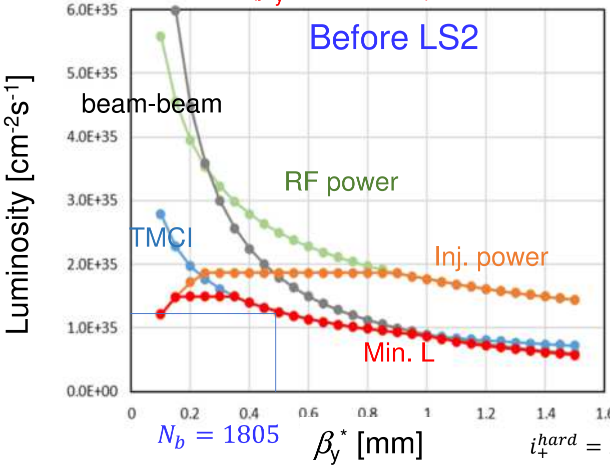
$I_+^{max} = 2.82$ A
$I_-^{max} = 2.04$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 30$ pm
$\xi_{y+}^{max} = 0.05$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

Luminosities under bunch-current limitations

- The maximum luminosities before and after LS2 were calculated using possible parameters.
    - Assumptions: full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%. (After Linac upgrade)
    - No background limit, Only Touschek lifetime.

- Larger ε_y, lower TMCI limit

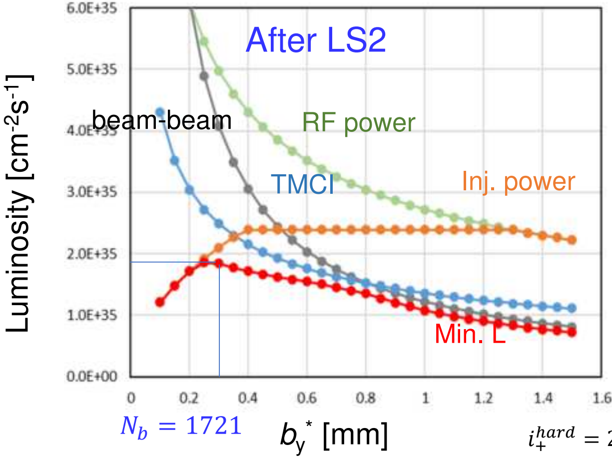
- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.2x10^35** [cm^-2s^-1]



$N_b = 1805$

$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 60$ pm
$\xi_{y+}^{max} = 0.04$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.0$ mA $\quad i_-^{tmci} = 1.2$ mA

- **After LS2**($\beta_y^* \geq 0.3$ mm), **L = 1.8x10^35** [cm^-2s^-1]



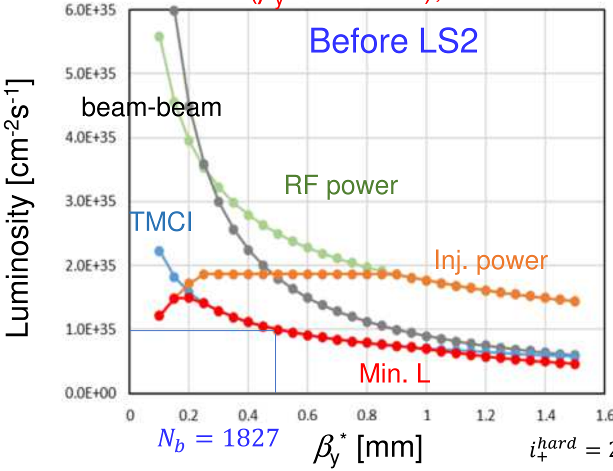
$N_b = 1721$

$I_+^{max} = 2.82$ A
$I_-^{max} = 2.04$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 30$ pm
$\xi_{y+}^{max} = 0.05$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.0$ mA $\quad i_-^{tmci} = 1.2$ mA

Luminosities under bunch-current limitations

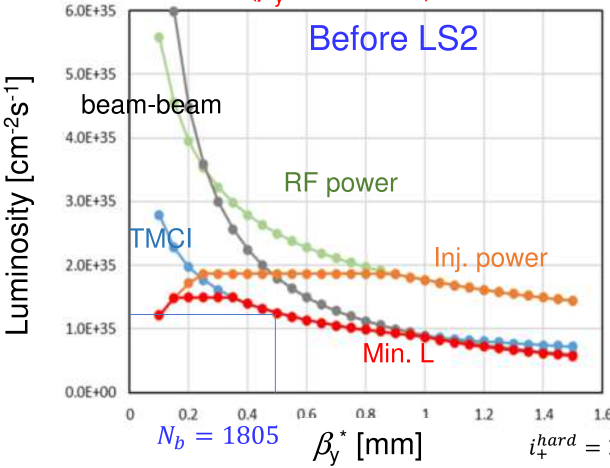
- The maximum luminosities before and after LS2 were calculated using possible parameters.
  - Assumptions: full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%. (After Linac upgrade)
  - No background limit, Only Touschek lifetime.
- Larger ε_y, much lower TMCI limit (LER)

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.0x10^35** [cm^-2s^-1]



$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 60$ pm
$\xi_{y+}^{max} = 0.04$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA
$i_+^{tmci} = 0.8$ mA $i_-^{tmci} = 1.2$ mA

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.2x10^35** [cm^-2s^-1]



$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 60$ pm
$\xi_{y+}^{max} = 0.04$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.0$ mA $i_-^{tmci} = 1.2$ mA

Trial re-estimation of luminosity profile

- Long-term luminosity profile was re-estimated based on recent findings, that is, luminosities under bunch-current limitations, various countermeasures proposed so far, and also recent operation experiences.

- Assumptions for re-estimation: Before LS2

(1) Injection power reaches to the designed one (4 nc/bunch, 2 bunch injection, 25 Hz, injection efficiency =0.8).
(2) LER beam lifetime will be 1.5 times higher than the present owing to the perfect matching.
(3) TMCI is improved by a factor of 1.5.
(4) Emittance will be improved to 20 pm. (TMCI limit might be not so important in this case)
(5) Beam lifetime will be limited by the Touschek effect. Actually, there will be other factors.
(6) β_y^* can be squeezed to 0.5 mm (as before)
(7) Maximum luminosity will be ~2×10^{35} $cm^{-1}s^{-1}$. (Cf. ~3x1035 MEXT RM)
(8) Operation efficiency will be 0.6, expecting some improvement.
(9) LS1 will be from July 2022 to May 2023.
(10) Eight months operation per year basically.
(11) LS2 will start from July 2026.
(12)Effective operation day is 28 days per month considering two maintenance days. It is assumed to be 20 days for months just after long break and those including β_y^*squeezing.

Trial re-estimation of luminosity profile

- Assumptions for re-estimation: After LS2

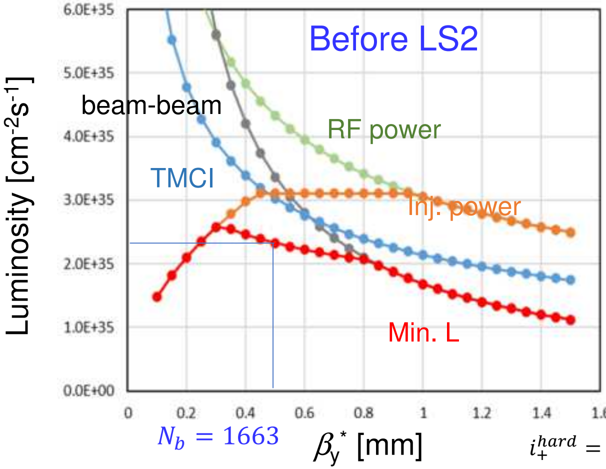
(1) Injection power is already the designed one (4 nc/bunch, 2 bunch injection, 25 Hz, injection efficiency =0.8).
(2) RF-system will be partially upgraded.
(3) β_y^* can be squeezed to down to 0.3 mm (as before)
(4) Beam lifetime will be limited by the Touschek effect.
(5) LER beam lifetime will be 1.5 times higher than the present owing to the perfect matching.
(6) QCSR beam pipe aperture will be enlarged. TMCI is improved by a factor of 1.5.
(7) Emittance will be improved to 10 pm. (TMCI limit might be not so important in this case)
(8) Maximum luminosity is ~3×10^{35} $cm^{-1}s^{-1}$. (Cf. MEXT RM assumed x2 luminosity upgrade)
(9) Operation efficiency will be 0.6, expecting some improvement.
(10) Eight months operation per year basically.
(11) LS2 will be from July 2026 to September 2027, 15 months.
(12) Effective operation day is 28 days per month considering two maintenance days. It is assumed to be 20 days for months just after long break and those including b_y^* squeezing.
(13) After LS2, starting β_y^* will be 3 mm. It takes one year to recover the machine performance before LS2 with β_y^* = 0.5 mm. It will take around two more years to squeeze β_y^* to around 0.3 mm and to achieve the goal luminosity.

Luminosities under bunch-current limitations

- The maximum luminosities before and after LS2 were estimated using possible parameters.
    - Assumptions: full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%. (After Linac upgrade)
    - Designed vertical emittance (No TMCI limit), No background limit, Only Touschek lifetime.

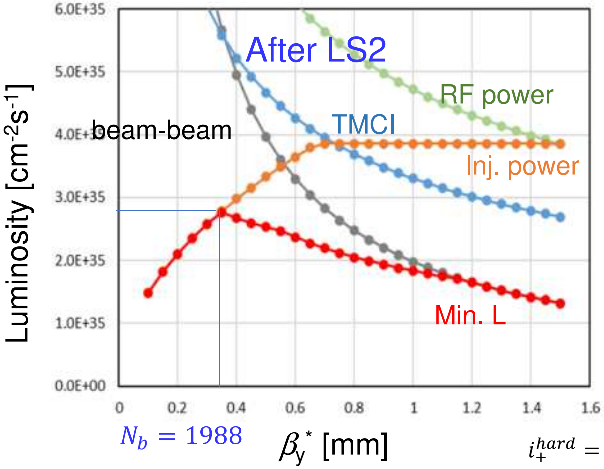
- Perfect match

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 2.3x10^{35}** [cm^{-2}s^{-1}]



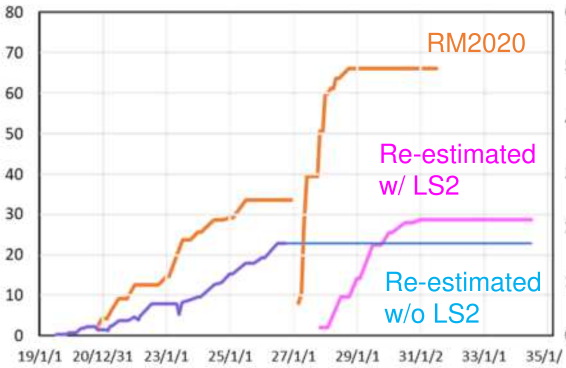
$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 20$ pm
$\xi_{y+}^{max} = 0.075$
$C_+^i = 5.4 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

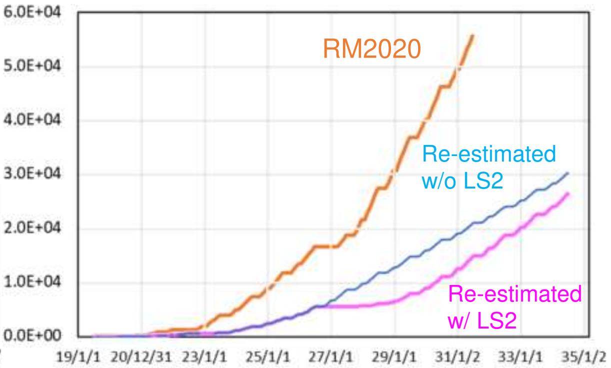
- **After LS2**($\beta_y^* \geq 0.3$ mm), **L = 2.8x10^{35}** [cm^{-2}s^{-1}]

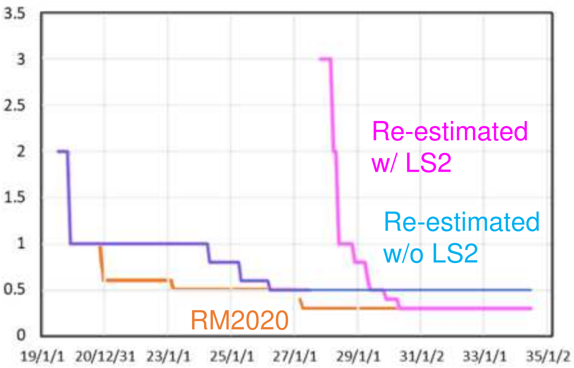


$I_+^{max} = 2.82$ A
$I_-^{max} = 2.04$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 10$ pm
$\xi_{y+}^{max} = 0.081$
$C_+^i = 5.4 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

- Re-estimated luminosity profile under new limitations.
  - Presented in RM2020, Re-estimated w/ and w/o LS2







- The estimated luminosity is lower than expected considering various limitations with the countermeasures discusses so far.
  - For the case of upgrade option #3, the intermediate upgrade of IR around 2026 seems not effective compared to the case without the upgrade from a viewpoint of int. luminosity.
- We continue to find more effective measures, not only limiting to IR but also including MR other parts and Linac.

Luminosities under bunch-current limitations

- Present parameters (Y. Ohnishi, 2021/7, BPAC)

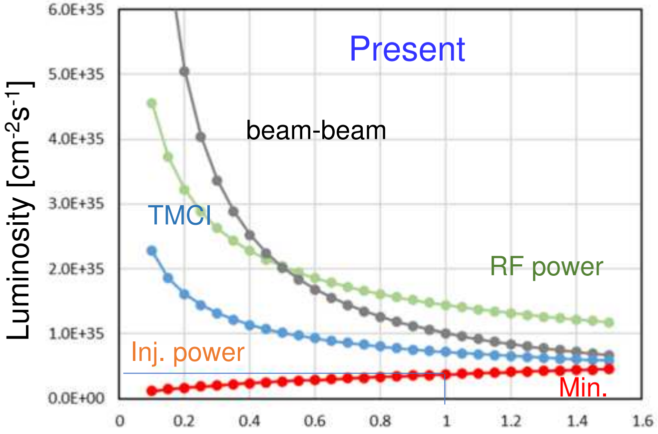
	2020b : June 21, 2020		2021b : June 22, 2021		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	712	607	**790**	**687**	mA
Number of bunches	978		1174		
Bunch current	0.728	0.621	0.673	0.585	mA
Lifetime	760	1270	540	1320	sec
Horizontal size σ_x*	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.403		0.324		μm*1
Vertical size σ_y*	0.285		0.229		μm*2
Betatron tunes ν_x / ν_y	45.523 / 43.581	44.531 / 41.577	44.524 / 46.596	45.532 / 43.581	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	10.7	12.7	
Crab Waist Ratio	80	40	80	40	%
Beam-Beam parameter ξ_y	0.039	0.026	0.046	0.030	
Specific luminosity	5.43×10^{31}		6.76×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.40×10^{34}		$\mathbf{3.12 \times 10^{34}}$		$cm^{-2}s^{-1}$

*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

5

Luminosities under bunch-current limitations

- **Luminosity under present condition**
  - Almost limited by injection power (beam lifetime).
    - **L = 3.7x10^{34} cm^{-2}s^{-1} (I_+= 970 mA, I_-=1020 mA)**



$N_b = 1013$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

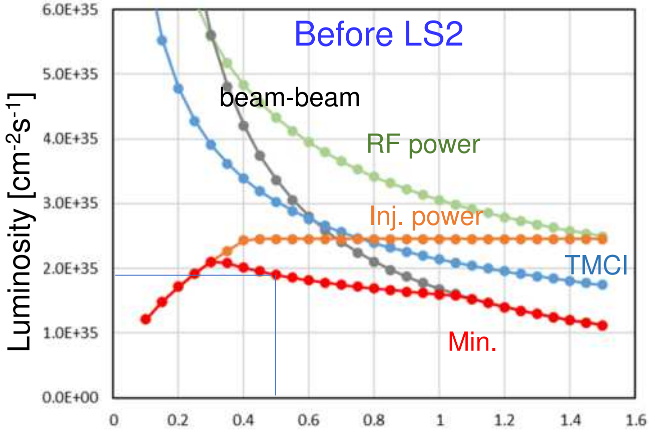
$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

$\epsilon_+^{inj} = 0.6$ $q_+^{inj} = 1.8$ nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 12.5$ Hz

$\epsilon_-^{inj} = 0.3$ $q_-^{inj} = 1.2$ nC $N_{b-}^{inj} = 1$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.0$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 1.9x10^{35} cm^{-2}s^{-1}**



$N_b = 1663$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 20$ pm $\xi_{y+}^{max} = 0.075$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

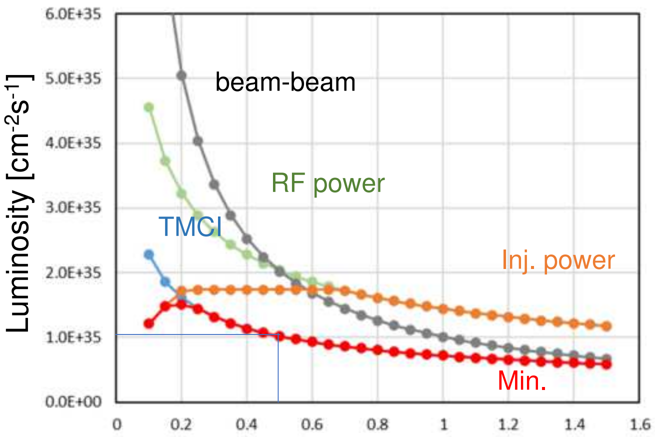
$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 4$ nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

Luminosities under bunch-current limitations

- Present condition **+ Full injection power**



$N_b = 1493$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

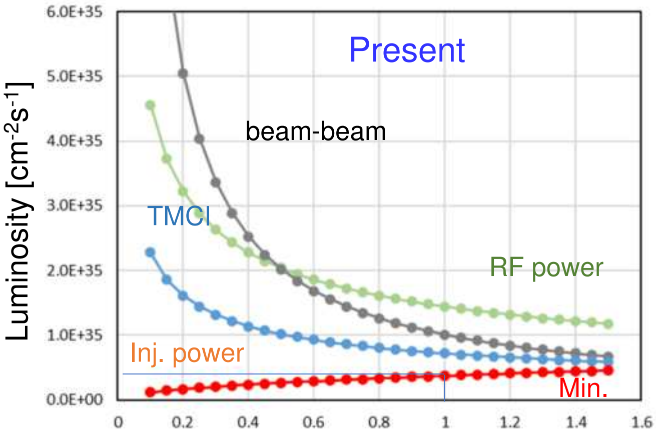
$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 4$nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.0$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2.$ mA $i_-^{hard} = 2$ mA

- **L = 1x10^{35} cm^{-2}s^{-1} (I_+=1490 mA, I_-=1870 mA)**

- Present condition



$N_b = 1013$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

$\epsilon_+^{inj} = 0.6$ $q_+^{inj} = 1.8$ nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 12.5$ Hz

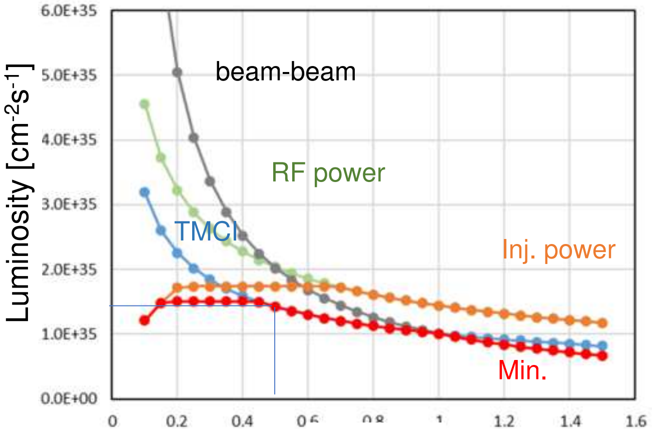
$\epsilon_-^{inj} = 0.3$ $q_-^{inj} = 1.2$ nC $N_{b-}^{inj} = 1$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.0$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 3.7x10^{34} cm^{-2}s^{-1} (I_+=970 mA, I_-=1020 mA)**

Luminosities under bunch-current limitations

- Present condition + Full injection power + **Higher TMCI limit**



$N_b = 1316$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

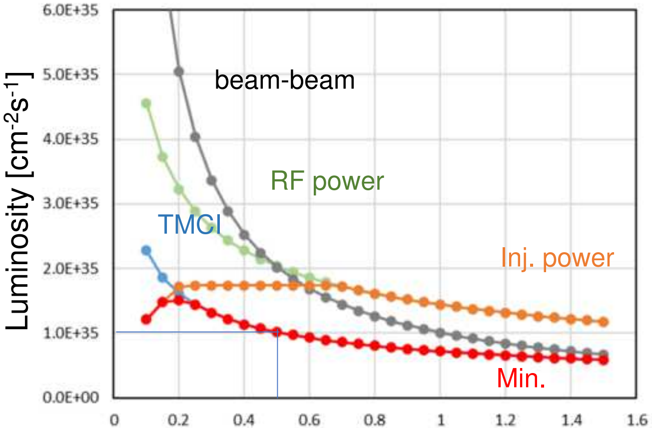
$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 4$ nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 1.4x10^{35} cm^{-2}s^{-1} (I_+=1840 mA, I_-=1870 mA)**

- Present condition + Full injection power



$N_b = 1493$ β_y^* [mm]

$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6 \times 10^7$ $C_-^i = 1.2 \times 10^8$

$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 4$ nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

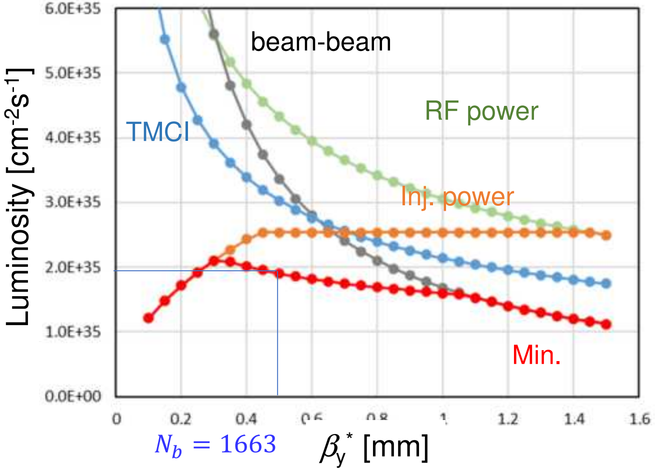
$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.0$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 1x10^{35} cm^{-2}s^{-1} (I_+=1490 mA, I_-=1870 mA)**

Luminosities under bunch-current limitations

- Present condition + Full injection power, higher TMCI **limit + lower emittance (higher b-b parameter)**



$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 20$ pm $\xi_{y+}^{max} = 0.075$ $C_+^i = 3.6\times10^7$ $C_-^i = 1.2\times10^8$

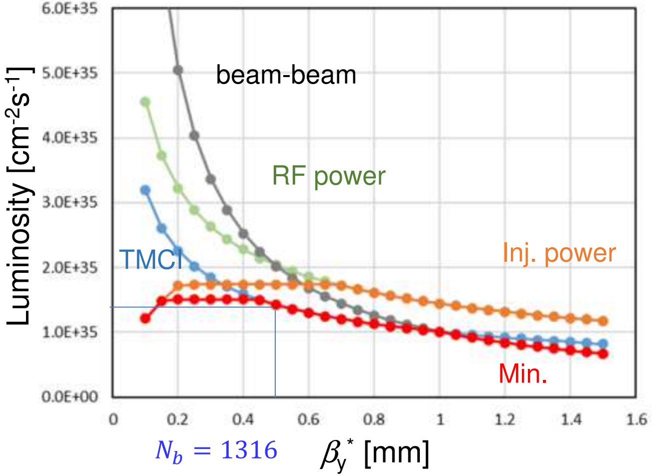
$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 24$nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 1.9x10[35] cm[-2]s[-1] (I_+=1460 mA, I_-=1870 mA)**

- Present condition + Full injection power + higher TMCI limit



$I_+^{max} = 2.59$ A $I_-^{max} = 1.87$ A $\sigma_z = 6.5$ mm $N_b^{max} = 2500$

$\varepsilon_y = 90$ pm $\xi_{y+}^{max} = 0.045$ $C_+^i = 3.6\times10^7$ $C_-^i = 1.2\times10^8$

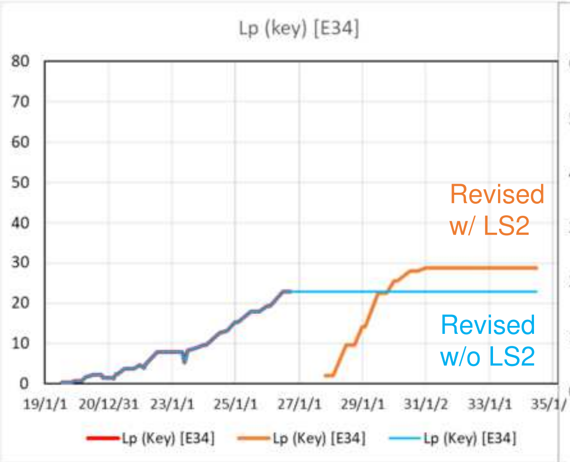
$\epsilon_+^{inj} = 0.8$ $q_+^{inj} = 24$nC $N_{b+}^{inj} = 2$ $f_{r+}^{inj} = 25$ Hz

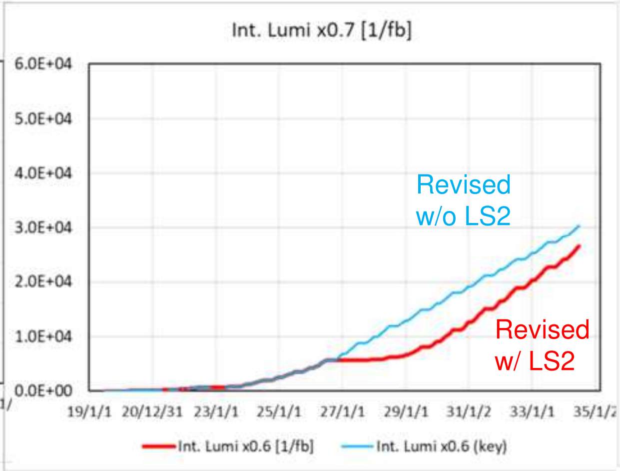
$\epsilon_-^{inj} = 0.8$ $q_-^{inj} = 4$ nC $N_{b-}^{inj} = 2$ $f_{r-}^{inj} = 25$ Hz

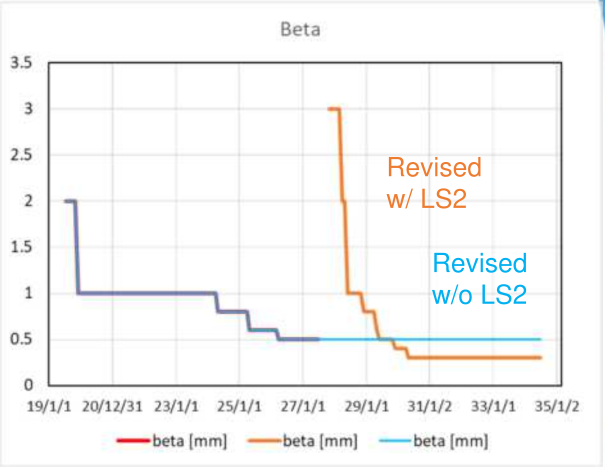
$i_+^{tmci} = 1.4$ mA $i_-^{tmci} = 1.5$ mA $i_+^{hard} = 2$ mA $i_-^{hard} = 2$ mA

- **L = 1.4x10[35] cm[-2]s[-1] (I_+=1840 mA, I_-=1870 mA)**

- **Revised luminosity profile**
  - Revised w/ LS2 and Revised w/o LS2

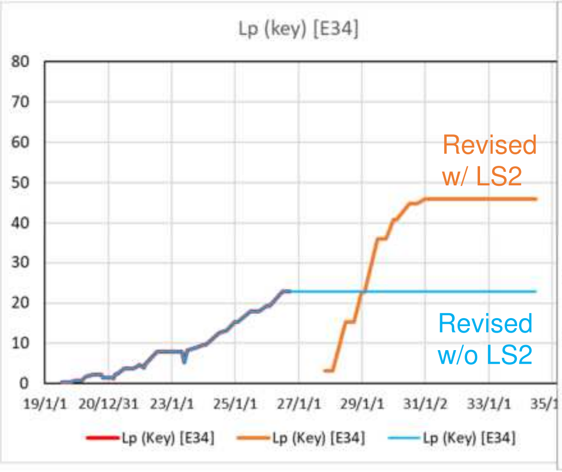


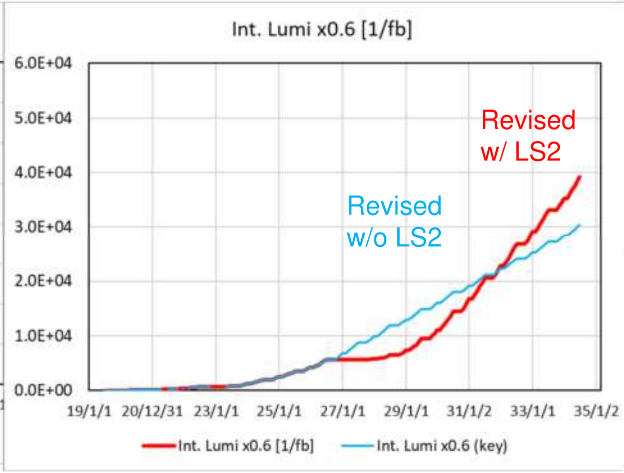


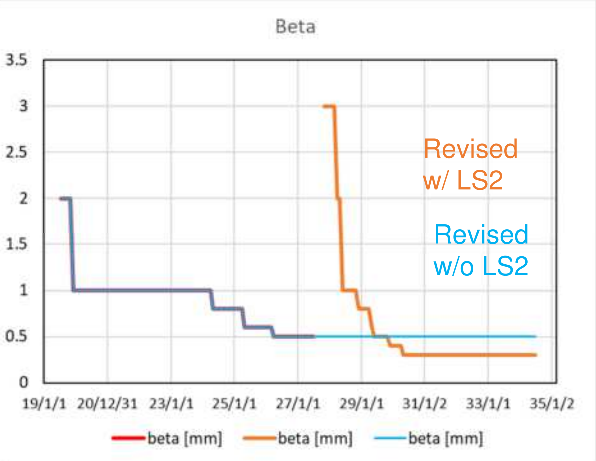


Trial re-estimation of luminosity profile

- **Revised luminosity profile**
  - Ref. Revised w/ LS2 (two times higher Luminosity after LS2) and Revised w/o LS2







- If we could boost up the luminosity to the twice of that before LS2 (~4.6x10^{35} cm^{-2}s^{-1}), the integrated luminosity will be almost the same around 2033.

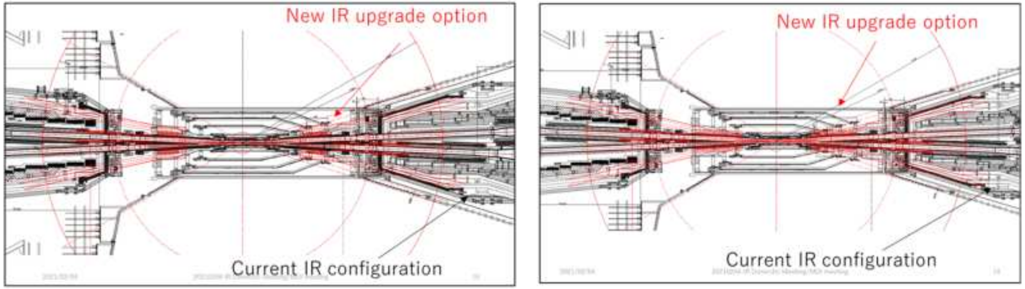
Countermeasures discussed so far

- For reference, proposed countermeasures **after LS2** (~2031?)
  - Still preliminary discussion

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Improve dynamic aperture	Large scale QCS **and also Belle II** modification (Option #8)	**LER beam lifetime x ~2.2**	Need further simulation	
Increase injection power (efficiency)	Linac upgrade **beyond designed specification**	**Injectin power x ~2?**	Need further invesitgation	

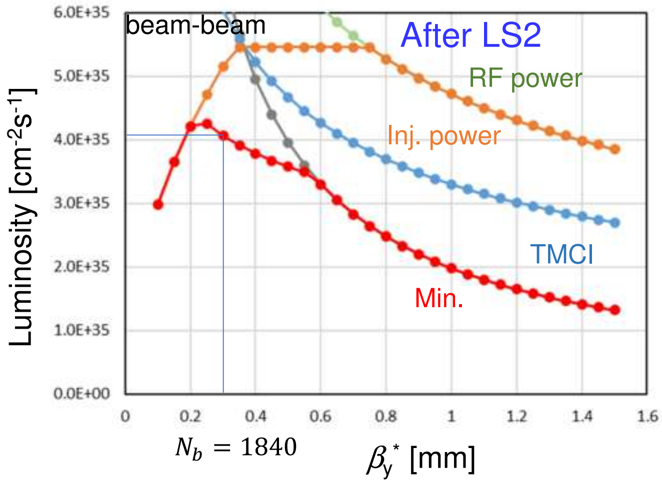
- With these countermeasures
- **L = ~2x10^{35} cm^{-2}s^{-1} → ~4x10^{35} cm^{-2}s^{-1}**

IR modification (option #8) including Belle II (SVD etc.)



Trial re-estimation of luminosity profile

- **With perfect match**
  - **If charge of injection beam x2**
    - **L = 4.1x10^{35} cm^{-2}s^{-1} (I$_+$=1740 mA, I$_-$=2040 mA)**



$I_+^{max} = 2.82$ A $\quad I_-^{max} = 2.04$ A $\quad \sigma_z = 6.5$ mm $\quad N_b^{max} = 2500$

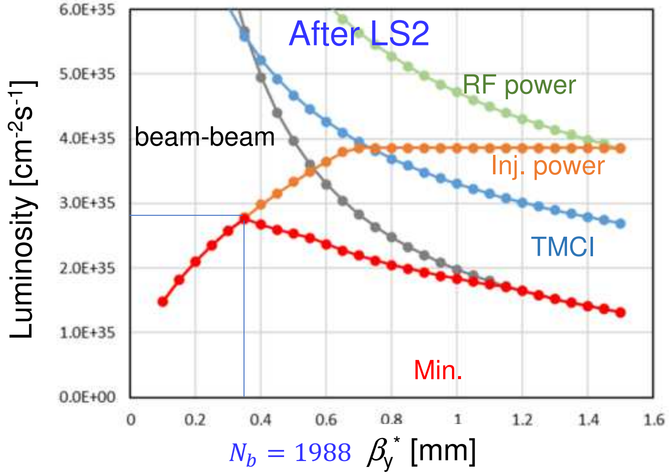
$\varepsilon_y = 10$ pm $\quad \xi_{y+}^{max} = 0.081 \quad C_+^i = 5.4 \times 10^7 \quad C_-^i = 1.2 \times 10^8$

$\epsilon_+^{inj} = 0.8 \quad q_+^{inj} = 8$ nC $\quad N_{b+}^{inj} = 2 \quad f_{r+}^{inj} = 25$ Hz

$\epsilon_-^{inj} = 0.8 \quad q_-^{inj} = 8$ nC $\quad N_{b-}^{inj} = 2 \quad f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA $\quad i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA

- **With perfect match**
  - LER lifetime x1.5
- **L = 2.8x10^{35} cm^{-2}s^{-1} (I$_+$=1380 mA, I$_-$=2040 mA)**



$I_+^{max} = 2.82$ A $\quad I_-^{max} = 2.04$ A $\quad \sigma_z = 6.5$ mm $\quad N_b^{max} = 2500$

$\varepsilon_y = 10$ pm $\quad \xi_{y+}^{max} = 0.081 \quad C_+^i = 5.4 \times 10^7 \quad C_-^i = 1.2 \times 10^8$

$\epsilon_+^{inj} = 0.8 \quad q_+^{inj} = 4$nC $\quad N_{b+}^{inj} = 2 \quad f_{r+}^{inj} = 25$ Hz

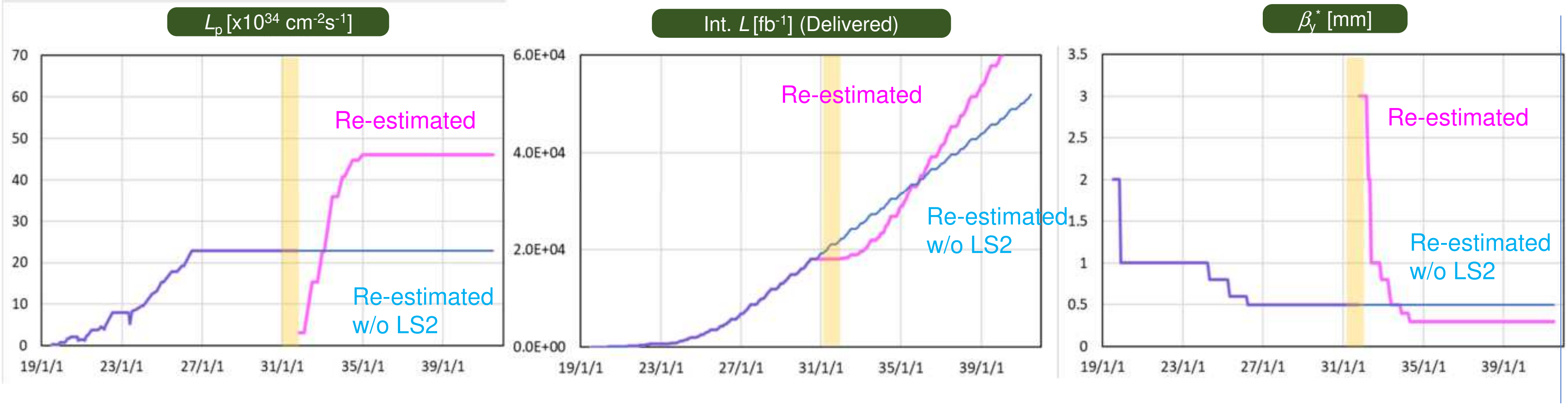
$\epsilon_-^{inj} = 0.8 \quad q_-^{inj} = 4$ nC $\quad N_{b-}^{inj} = 2 \quad f_{r-}^{inj} = 25$ Hz

$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA $\quad i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA

- The same effect for twice longer beam lifetime

Trial re-estimation of luminosity profile

- Re-estimated luminosity profile
  - If we could have a long shutdown around 2031 and boost up the boost up the luminosity by a factor of 2, from ~2x10^{35} to =~4x10^{35} cm^{-2}s^{-1};



- We need to continue to search effective measures like that.

Appendix E: Task force

Task force

- Members
  - ARC members prepared a list of possible candidates in June, 2021, following the requirement from the management of the KEK Accelerator Lab. and B promotion office (BPO).
  - Initial members have been identified through the discussion with KEKB commissioning team.
  - Coordinator: M. Masuzawa (KEK)
  - More members who have required expertise and strong interest are welcome.

International Task Force members

2021/7/27

International members

Maria Enrica Biagini	INFN
Georg Hoffstaetter	Cornell
Evgeny Levichev	BINP
Mark Palmer	BNL
Yunhai Cai	SLAC
Rogelio Tomas	CERN
Pantaleo Raimondi	ESRF
Katsunobu Oide	CERN/KEK

KEK ACCL members

Mika Maszawa (Chair)	SKEKB
Yukiyoshi Ohnishi	SKEKB
Akio Morita	SKEKB
Hiroshi Sugimoto	SKEKB
Renjun Yang	SKEKB
Haruyo Koiso	SKEKB
Yoshihiro Funakoshi	SKEKB
Tsukasa Miyajima	SKEKB
Kazuhito Ohmi	SKEKB
Demin Zhou	SKEKB
Kentaro Harada	KEK-PF

Belle II members

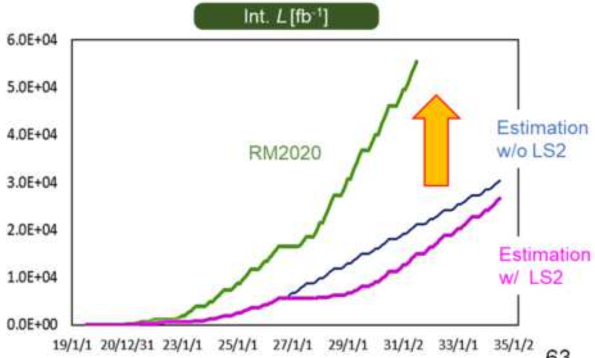
Hiroyuki Nakayama	Belle II
Francesco Forti	Belle II

BPO members

Masanori Yamauchi	KEK		
Tadashi Koseki	ACCL	Naohito Saito	IPNS
Makoto Tobiyama	SKEKB	Shoji Uno	Belle II
Kazuro Furukawa	SKEKB	Yutaka Ushiroda	Belle II
Kyo Shibata	SKEKB	Toru Iijima	Belle II
Yusuke Suetsugu	SKEKB	Kodai Matsuoka	Belle II

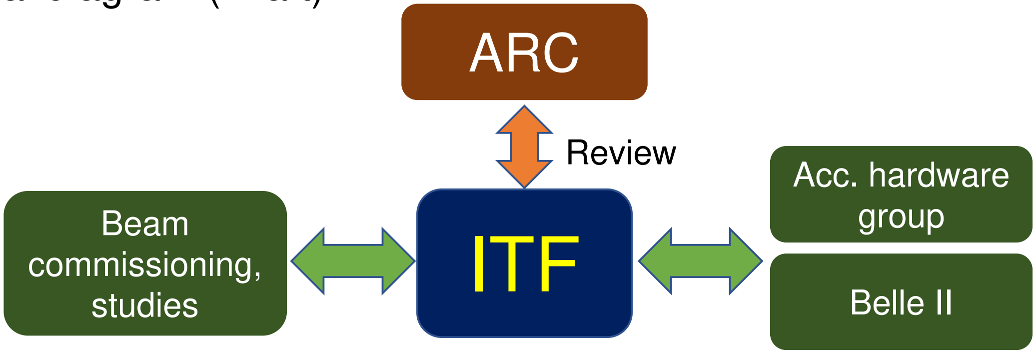
Task force

- Charges
  - Consider effective ideas to realize luminosity of ~6x10^{35} cm^{-2} s^{-1} as a result of an intermediate upgrade around 2026, which could include modifications of IR, final focus systems, injectors, but without changing the boundary to the Belle II detectors.
  - Find a realistic way before long shutdown 1 (LS1) scheduled to start Jul/2022 in order to achieve luminosity of the order of 10^{35} cm^{-2} s^{-1} without large modification of accelerator components.
  - Consider longer-term alternative idea to achieve ~6x10^{35} cm^{-2} s^{-1} or more, even by largely modifying the IR and the Belle II detector.



Task force

- Standing position and main role
  - Conceptual diagram (Draft)



"Hands on" work is required

- Proposals of new ideas
  - Countermeasures against challenges
  - Study plans, commissioning plans (strategies)
- Simulations
  - Beam-beam, optics, instabilities, etc.
- Participation in the commissioning
  - Remote for the time being, on site (after Covid-19)
- Discussions and comments on various issues

Task force

- Activity period
  - Coming one year, before the LS1.
- Rough schedule
  - (Online) meeting per month basically.
  - Meetings are basically open, but may occasionally have closed sessions.
  - Special review by ARC per ~6 months.
  - Final report is to be submitted by the end of July, 2022.

	2021						2022						
	7	8	9	10	11	12	1	2	3	4	5	6	7
Meeting	○ Kick off	○		○	○	○		○	○		○	○	
Review by Arc			○				○			△ As needed			○ Report
Machine operation													

Task force

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Meeting	○ Kick off	○		○	○	○		○	○		○	○	
Review by Arc			○				○			△ As needed			○ Report
Machine operation													

Task force

- Subgroups (as of August 2021)

1) beam-beam
   - Contact person : Demin Zhou <dmzhou@post.kek.jp>
   - Sub : Kazuhito Ohmi <ohmi@post.kek.jp>
   - Mailing list skb-itf-bb@ml.post.kek.jp

2) optics
   - Contact person : Akio Morita <akio.morita@kek.jp>
   - Sub : Haruyo Koiso <haruyo.koiso@kek.jp>
   - Mailing list skb-itf-opt@ml.post.kek.jp

3) TMCI and impedance matters
   - Contact person: Rogelio Tomas Garcia
   - Sub: Takuya Ishibashi
   - Mailing list skb-itf-tmci@ml.post.kek.jp

Backup

Near-term operation plan and luminosity profile

- Operation schedule (from the last BPAC, 2021/3/1)
  - **FY2021**
    - Now we finished 2021b run, and are in the summer shutdown
    - 2021c run will start on 19th October, and end 23rd December (fixed).
    - 2022a run will start on 9th February, and end at the end of March (not fixed, depends on budget, etc.). Then the total operation period will be ~7 months.

Now

	2021									2022			
FY2021	4	5	6	7	8	9	10	11	12	1	2	3	
	4/1	2021b ~3.1M		7/5			10/19	2021c ~2.2M	12/23		2/9	2022a ~1.7M	**Total ~7.0M/y**
	2022									2023			
FY2022	4	5	6	7	8	9	10	11	12	1	2	3	
	4/1	2022b ~3.5M		7/15	LS1								**Total ~3.5M/y**
	2023									2024			
FY2023	4	5	6	7	8	9	10	11	12	1	2	3	
	LS1	5/15	2023b ~2M	7/15			10/9	2023c ~2.5M	12/22		2/9	2024a ~1.7M	**Total ~6.2M/y**

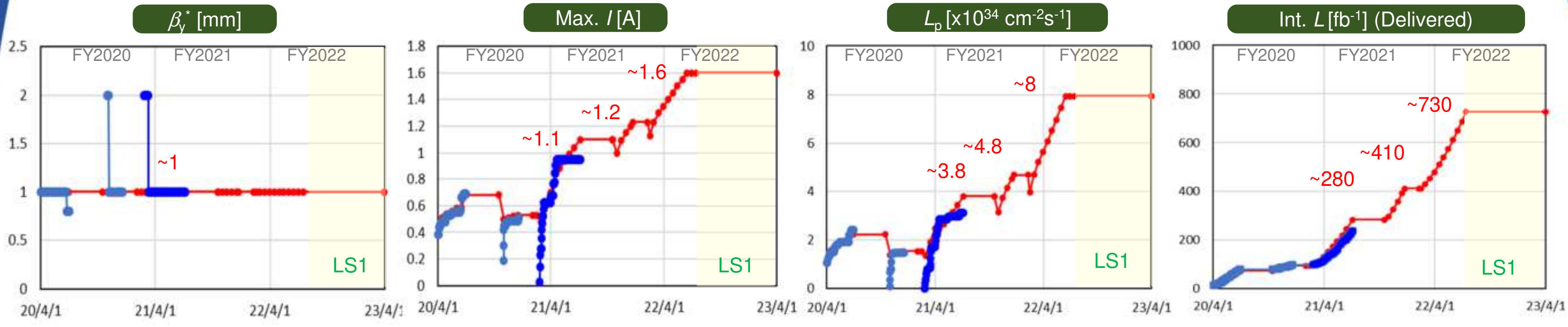
Near-term operation plan and luminosity profile

- Operation schedule (from the last BPAC, 2021/3/1)
  - **FY2022 (Not yet fixed)**
    - 2022b run will start on 1st April, and end in the middle of July
    - The PXD exchange work (LS1) is scheduled to start from July, but it is fluid depending on the situations of COVID-19 and also budget.
      - A possible schedule is to start LS1 from January, 2023.
    - Here we assume the present schedule, then the total operation period will be ~3.5 months.

	2021									2022			
FY2021	4	5	6	7	8	9	10	11	12	1	2	3	
	4/1	2021b ~3.1M		7/5			10/19	2021c ~2.2M	12/23		2/9	2022a ~1.7M	Total ~7.0M/y
	2022									2023			
FY2022	4	5	6	7	8	9	10	11	12	1	2	3	
	4/1	2022b ~3.5M		7/15	LS1								Total ~3.5M/y
	2023									2024			
FY2023	4	5	6	7	8	9	10	11	12	1	2	3	
	LS1	5/15	2023b ~2M	7/15			10/9	2023c ~2.5M	12/22		2/9	2024a ~1.7M	Total ~6.2M/y

Results so far

- Results of 2020/4/1~2021/7/5 (Blue pints)



- β_y^* = 1 mm
- Max. luminosity = 3.12x10^{34} cm^{-2}s^{-1} (5/17)
- Int. luminosity (Delivered, 2019c ~ 2021/7/5) = 235 fb^{-1}
- Max. beam current $\sqrt{I_+ I_-}$ = 0.83 A (4/20) [HV on] (0.95 A (4/20) [HV off])
- Max. 7-days int. luminosity (Recorded) = 12.4 fb^{-1} (5/14～5/20)
- Max. daily int. luminosity (Recorded) = 1964 pb^{-1} (5/18)
- All values exceeded the records of KEKB

Works planed in this summer shutdown

- Regular maintenance (Water flow meters, Power supplies for RF and magnets, etc.
- Collimators
  - Replacement of 2 collimator heads (HER).
  - Upgrade of driving device of 2 collimators (HER)
  - Installation of new collimator heads with 3 mm Tantalum and graphite (at LER arc).
    - Robust against damages from beam.
  - Relocation of LER D02V1 collimators? (under discussion)
- Exchange of the mirror and its folder of SR beam size monitor for LER.
- Installation of a HOM absorber at RF section (HER Nikko).
- BT
  - Installation of beam profile monitors with OTR screen.
  - Installation of a beam shutter in LER injection line.
- Installation of a strip-line kicker into RTL line at DR
- Anti-aging measures
  - Replacement of HV (66 kV and 6.6 kV) power cables.
  - Repair of water leak from roof of some power stations.
  - Replacement of some old water pumps.

Summaries of near-term operation plan

- Near-term operation plan and luminosity profile
  - The operation is in progressing almost as planned.
    - Seven months operation is planed in this fiscal year.
    - Budget request for FY2022 is on going.
  - The maximum beam currents, the peak luminosity are almost as expected.
    - Number of bunches was increased to 1272.
    - We are in the midst of replacing the highest records.
  - Integrated luminosity, however, was ~70% of the expected one.
    - Operation efficiency is around 0.5, not 0.65.
    - If the machine is stable, the operation efficiency of over 0.65 is achievable.
- We will basically keep the present operation plan and luminosity profile, making best effort to catch up with the target values.

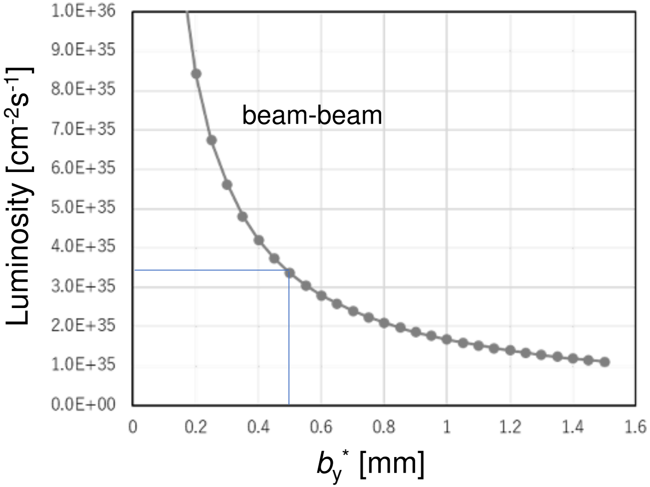
Designed luminosity

- **Assumptions in the present luminosity profile: Before LS2**
- The maximum beam-beam parameter (ξ_{y+}^{max}) was assumed to be 0.075.
- β_y^* will be squeezed to 0.5 mm before LS2.
- Luminosity was determined by the beam-beam parameter.
- Beam currents were determined by RF power.

$$\xi_{y+}^{max} = 0.075$$

$$L_\xi = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_{y\mp}^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*} \sim \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$

$$I_+^{max} = 2.59\ [\mathrm{A}],\ I_-^{max} = 1.87\ [\mathrm{A}]$$



$$I_+^{max} = 2.59\ [\mathrm{A}],\ I_-^{max} = 1.87\ [\mathrm{A}]$$

$$\xi_{y+}^{max} = 0.075 \qquad N_b^{max} = 2500$$

- At β_y^*=0.5 mm,

$$L_{bb}^{max} = 3.4\times 10^{35}\ \ [\mathrm{cm^{-1}s^{-1}}]$$

- $$L = \frac{1}{4\pi e^2 f_0 \sin\phi_c \sigma_z}\frac{N_b i_{b+} i_{b-}}{\sqrt{\beta_y^* \varepsilon_y}}$$

$$N_b = 1565 \quad \sigma_z = 6.5\ [\mathrm{mm}]$$
$$i_{b+} = 1.65\ \ [\mathrm{mA\ bunch^{-1}}]$$
$$i_{b-} = 1.19\ \ [\mathrm{mA\ bunch^{-1}}]$$
$$\varepsilon_y = 19.7\ [\mathrm{pm}]$$

Designed luminosity

- **Assumptions in the present luminosity profile: After LS2**
- The maximum beam-beam parameter (ξ_{y+}^{max}) was assumed to be 0.081.
- β_y^* will be squeezed to 0.3 mm finally.
- Luminosity was determined by the beam-beam parameter.
- Beam currents were determined by RF power. Need partial RF-system upgrade.

$$\xi_{y+}^{max} = 0.081$$

$$L_\xi = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_{y\mp}^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*} \sim \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$

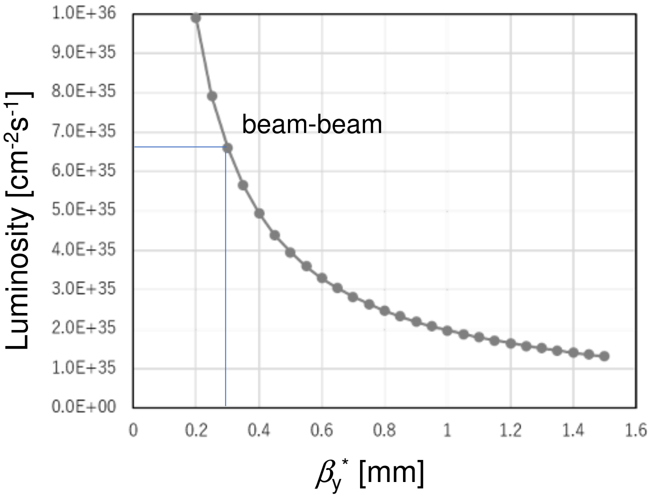
$$I_+^{max} = 2.82\ [\mathrm{A}],\ \ I_-^{max} = 2.04\ [\mathrm{A}]$$

- At β_y^*=0.3 mm,

$$L_{bb}^{max} = 6.6 \times 10^{35}\ \ [\mathrm{cm^{-1}s^{-1}}]$$

- $L = \dfrac{1}{4\pi e^2 f_0 \sin\phi_c \sigma_z}\dfrac{N_b i_{b+} i_{b-}}{\sqrt{\beta_y^* \varepsilon_y}}$

$N_b = 1761$ $\sigma_z = 6.5$ [mm]
$i_{b+} = 1.60$ [mA bunch^{-1}]
$i_{b-} = 1.16$ [mA bunch^{-1}]
$\varepsilon_y = 10.8$ [pm]



$I_+^{max} = 2.82$ [A], $I_-^{max} = 2.04$ [A]

$\xi_{y+}^{max} = 0.081$ $N_b^{max} = 2500$

End